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SEAT DESIGN FOR CRASH WORTHINESS

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SUMMARY

From a study of many crash deceleration records, a simplified model of a crash deceleration pulse is suggested which incorporates the essential properties of the pulse. The model pulse is considered to be made up of a base pulse on which are superimposed one or more secondary pulses of shorter duration. The results of a mathematical analysis of the seat-passenger deceleration in response to the airplane deceleration pulse is provided. On the basis of this information, presented as working charts, the maximum deceleration loads experienced by the seat and passenger in response to the airplane deceleration pulse can be computed. This maximum seat-passenger deceleration is found to depend on the natural frequency of the seat containing the passenger, considered as a mass-spring system.

Seat failure is considered to be a progressive process, which begins when the seat is deformed beyond the elastic limit. Equations are presented which relate the energy available to deform the seat beyond the elastic limit to the maximum seat-passenger deceleration, seat natural frequency, and seat strength. A method is presented that shows how to arrive at a combination of seat strength, natural frequency, and ability to absorb energy in deformation beyond the elastic limit to allow the seat to serve without failure through an airplane deceleration pulse taken as the design requirement. These qualities of the seat can be obtained from measurements made under static conditions.

Data are presented from full-scale laboratory and crash studies on the deceleration loads measured on dummy passengers in seats of standard and novel design. The general trends indicated by theory are obtained.

INTRODUCTION

Crash measurements show that the deceleration imposed on the seat in a crash is highly irregular, and the question is raised "What is the relation between the properties of a seat measured under static conditions and its ability to hold the passenger through this deceleration?" The first part of this paper is concerned with the answer to this question.

Crash measurements showed periods of high deceleration lasting for several tenths of a second separated by longer time intervals during which the deceleration was below 3 or 4 g's. Since airplane seats are built to withstand deceleration loads above 9 g's, seat failure will usually occur during the short-duration high-deceleration phase of the crash. For this reason, interest in this paper centers on this high-deceleration phase. A typical crash record of this high-deceleration period is shown in figure 1(a). Its highly oscillatory and irregular character is apparent.

The seat is the structural link between the fuselage floor and the passenger. The force required to decelerate the passenger is applied by the seat, usually through the seat belt or seat back. If the passenger were fastened rigidly to the seat and the seat rigidly to the floor, then the passenger, seat, and floor would move as a unit. The deceleration shown in figure 1(a), measured on the floor, would appear everywhere on the seat and passenger. The seat deceleration loads would be known at once from the measured floor deceleration. If the peak deceleration here were 10 g's and the seat were designed for 12 g's, the seat would be working within safe limits. Actually, however, the seat is not rigid. It is made of flexible members. Also, the passenger is loosely connected to the seat at the moment of crash.

Seat flexibility is considered first, and the passenger is assumed tightly coupled to the seat. The passenger and the seat form a mass-spring system indicated schematically in figure 2(a). The pedestal of the seat forms the spring attached to the floor, and the passenger constitutes the mass. When the passenger sits lightly in the seat, it has its normal shape. However, when the seat restrains the passenger with a large holding force in a crash, the seat distorts, as shown in exaggerated form in figure 2(b). The holding force F on the passenger grows as the seat distorts in the manner shown in figure 3. The straight-line portion of the curve is given by the expression

$$F = kx \tag{1}$$

where k is the elastic constant of the seat and x is the seat distortion. The important point is that the passenger-holding force develops as the seat distorts, and this distortion takes time to grow.

For the purpose of this paper, the design strength of the seat is defined as the force F_d that distorts the seat to its elastic limit x_d. The term x_d is called the design distortion. As long as the seat distortion remains within the elastic limit, it will return to its original shape when the holding force F is relieved. If x_d is exceeded, then the seat is permanently deformed. The process of seat failure has begun. Seat failure is considered to be a progressive process in which the permanent deformation of the seat grows to the point where the link between the passenger and the floor is broken.

The design strength of a seat is often quoted in terms of the passenger deceleration the seat will hold, expressed in gravitational units. If M is the mass of the passenger, then the design strength of the seat $A_{s,d}$ expressed in gravitational units is $A_{s,d} = F_d/M$, where F_d is given in pounds-force and M is given in pounds-mass. For simplicity, the seat is taken to be without mass compared with the passenger, who is assumed to weigh 200 pounds. The seat distortion x is measured at the point of application of the passenger-holding force. For a forward-facing passenger, this point is the seat-belt-attachment fitting on the seat. For a rearward-facing passenger, the holding force is distributed over the seat back as shown in figure 2(b). The point at which the seat distortion should be measured is determined by the moment of the passenger's mass with respect to the seat floor attachment. This point is approximately 1 foot above the seat pan.

Data indicate that the natural frequency of a seat carrying a 200-pound passenger would be less than 20 cycles per second. From theory, it is known that spring-mass systems having this low natural frequency will not move appreciably in response to the high-frequency components of the floor deceleration, which are of the order of 100 cycles per second in figure 1(a).

If these unimportant high-frequency oscillations in the deceleration trace are filtered out and only those oscillations up to 50 cycles per second are left, the prominent features of the deceleration trace become evident in figure 1(b). The main crash pulse in this case appears to be made up of a base pulse of about 0.6-second duration surmounted by a few short-duration secondary pulses that rise to about twice the magnitude of the base pulse. In general, the deceleration can be considered to be composed of a base pulse having one or more secondary pulses, which may be of a magnitude greater or less than the base pulse. The secondary pulses may occur anywhere on the base pulse. Because the actual deceleration cannot be specified more exactly, a model for the deceleration is adopted which is made up of a base pulse and a secondary pulse timed to produce the maximum seat load. This time will vary according to the case and need not be specified now. Seats designed to withstand this model deceleration best will also serve best in an actual crash.

SYMBOLS

A magnitude of deceleration, g's ($A_s = A_{s,max}$)

a deceleration, function of time, g's

E energy of seat distortion, ft-lb

F seat-holding force, lb

f_a frequency of airplane deceleration half-sine pulse, cycles/sec

f_n natural frequency of seat-passenger system, cycles/sec

k elastic constant of seat, lb/ft

M mass of passenger, lb

T period of natural oscillation of seat-passenger system, $1/f_n$

t time, sec

V airplane velocity, ft/sec

Δv relative velocity between seat and airplane, ft/sec

x seat distortion, ft or in.

τ airplane deceleration rise time, sec

Subscripts:

a airplane

d design

max maximum

s seat

SEAT RESPONSE TO DECELERATION PULSE

The immediate concern is the response of the passenger and seat to the prominent deceleration pulse. To simplify the present discussion, only the main base pulse is considered, assuming that it is a sine wave running for one-half of 1 complete cycle. It is instructive to compare how the fuselage floor supporting the seat and the seat behave in response to this deceleration. In the remainder of this discussion, the term airplane deceleration is considered to be synonymous with fuselage-floor deceleration and seat deceleration to be synonymous with passenger deceleration.

Airplane-Seat Deceleration Relation

In the upper part of figure 4 is shown the half-sine airplane deceleration pulse as a function of time. The lower part shows the airplane velocity during the pulse. At the beginning of the deceleration the

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airplane has an initial velocity indicated by the intercept of the velocity curve with the ordinate axis. As the airplane decelerates, its velocity falls, the slope of the velocity curve at any time being equal to the magnitude of the deceleration at the same time. The rate of change of the velocity is a maximum when the deceleration peaks. When the deceleration is over, the airplane velocity is reduced by an amount numerically equal to the area under this deceleration-time curve.

Now consider the passenger in a rearward-facing seat, chosen rearward only because it eliminates the complicating factor of passenger flexure over the seat belt that occurs in a forward-facing direction. At the onset of the airplane deceleration, the seat distortion is small because this distortion requires time to develop. The passenger-holding force and, consequently, his deceleration are small also. The passenger velocity exceeds the airplane velocity by virtue of the lower passenger deceleration. At the point where the airplane and passenger decelerations cross, both have the same deceleration and the velocity curves are parallel. After the airplane deceleration is over, the airplane moves with uniform velocity, but the passenger continues to decelerate because he has a velocity higher than that of the airplane. At the peak of the passenger deceleration curve, the seat has its maximum distortion and the passenger attains the velocity of the airplane. As the elastic deformation of the seat subsides, the decelerating force still acts on the passenger, and his velocity drops below the airplane velocity.

The point of maximum seat stress occurs when the seat distortion is greatest. This point is at the top of the passenger deceleration curve. As this point is approached, the seat is in greatest danger of failure. For this reason, in the discussion that follows attention is fixed on this point of maximum passenger deceleration.

The time lag between the peak airplane and peak seat decelerations is related to the maximum velocity acquired by the seat with respect to the airplane in the following way: The seat velocity, with respect to the airplane, increases as long as the seat deceleration is less than that of the airplane. If the airplane and seat decelerations are plotted on the same time base, as in figure 5, the area between the airplane and seat deceleration curves shows the variation of the relative seat velocity with time. Starting at zero time, the seat deceleration is less than the airplane deceleration until time $t = T_1$ is reached when the two deceleration curves cross. The velocity acquired by the seat with respect to the airplane is given by the expression

$$\Delta v = \int_{t=0}^{t=T_1} (a_a - a_s)\, dt \tag{2}$$

This integral is numerically equal to the shaded area between the two deceleration curves to the left of their intersection point (fig. 5).

The relative seat velocity Δv decreases when the seat deceleration rises above the airplane deceleration after time $t = T_1$. As long as Δv is positive, the seat distortion will grow. The passenger-holding force and, consequently, the seat deceleration will increase with this distortion in accordance with the previous discussion. The seat deceleration will increase, therefore, until all the relative seat velocity acquired before $t = T_1$ is cancelled during the higher-seat-deceleration phase after $t = T_1$. The seat deceleration will reach its maximum when Δv falls to zero, and the increase in seat distortion ends at time $t = T_2$. Since the relative velocity acquired up to $t = T_1$ has been cancelled in the time $T_2 - T_1$, then

$$\int_{t=0}^{t=T_1} (a_a - a_s)\, dt = \int_{t=T_1}^{t=T_2} (a_s - a_a)\, dt \tag{3}$$

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The peak seat deceleration occurs when the area between the seat and airplane deceleration curves to the right of their intersection is equal to that to the left. This is a useful point of view to establish in considering this subject.

The question that now arises is, "What determines whether the peak passenger deceleration is less than, equal to, or greater than the peak airplane deceleration?" A mathematical analysis shows that the relative magnitudes of the passenger and airplane decelerations depend on the ratio of the natural frequency of the seat to the frequency of the half-sine-wave deceleration pulse. This frequency is taken to be equal to that of the continuous sine wave from which the airplane half-wave deceleration pulse is taken.

The dependence of maximum seat deceleration on frequency ratio appears in figure 6(a). Plotted along the abscissa is the ratio of seat natural frequency to airplane deceleration frequency, and along the ordinate is the ratio of peak seat deceleration to peak airplane deceleration. The peak passenger deceleration is less than the peak airplane deceleration as long as the frequency ratio is less than 0.52. Between a frequency ratio of 0.52 and 5.0 the peak passenger deceleration is greater than that of the airplane. The peak passenger deceleration can be nearly 1.8 times the peak airplane deceleration. For frequency ratios above 5, the peak passenger and airplane decelerations are about equal.

It will be useful in future discussion to replot the data in figure 6(a) in the form shown in figure 6(b), in which the airplane deceleration frequency is the ordinate and the natural frequency of the seat is the abscissa. Lines of constant frequency ratio f_n/f_a are straight lines in this plot. To each of these lines, a value for A_s/A_a is assignable from the original plot (fig. 6(a)). The zones of attenuated, amplified, and normal passenger response are mapped as wedge-shaped zones. This

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plot shows that a seat with a low natural frequency will operate in the amplification zone over a narrower range of airplane deceleration frequencies than the stiffer seats of high natural frequency. The stiffer seats have the advantage of operating in the normal zone for a wider range of airplane deceleration frequencies.

Factors Governing Natural Frequency of Seat

Two seat-design factors govern seat natural frequency: design seat strength F_d and the seat distortion x_d that occurs under a load equal to F_d. The natural frequency of the seat is given by the expression

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{M/32}} \tag{4}$$

where $k = F_d/x_d$ and $M = 200$ pounds $= 200/32$ slugs. When these substitutions are made, equation (4) has the form

$$f_n = \frac{1}{2\pi}\sqrt{\frac{F_d}{x_d M/32}} = \frac{1}{2\pi}\sqrt{32\frac{A_{s,d}}{x_d}} \tag{5}$$

since $F_d/M = A_{s,d}$. The variation of seat natural frequency with seat strength and deformation given by equation (5) is plotted in figure 7. If the design distortion x_d is 1 inch, the natural frequency of the seats ranges from 7 to 17 cycles per second for seats ranging in strength from 5 to 30 g's. If the design distortion is increased to 12 inches, about the practical maximum for airplanes, the natural frequency declines to 2 cycles per second for the 5-g seat and 5 cycles per second for the 30-g seat. In general, most aircraft seats carrying a 200-pound passenger will have a natural frequency less than 20 cycles per second.

Seat Response to a Base Deceleration Pulse

A brief study of the seat response to a single half-sine pulse raises some important aspects of the seat-design problem. In this study the effect of the duration of the deceleration pulse on the maximum seat deceleration is examined.

Two of the several factors defining the severity of a deceleration pulse are the airplane velocity change that occurs over the pulse and the peak deceleration attained. If the pulse has a pure half-sine form, the change in airplane velocity ΔV is given by the expression

$$\Delta V = \frac{2}{\pi} A_a t \tag{6a}$$

where A_a is the amplitude of the airplane half-sine deceleration pulse, expressed in feet per seconds squared and t is the total pulse duration. Since the period of the sine wave from which the half-sine pulse is taken is equal to $2t$, the frequency f_a is equal to $1/2t$. Substitution of this equality in equation (6a) yields the useful equation

$$\Delta V = \frac{A_a}{\pi f_a} \tag{6b}$$

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The change in airplane velocity during a pulse is plotted in figure 8 with the ordinate scale linear for f_a and a linear abscissa scale for A_a. A second ordinate scale for the time duration of the pulse t is nonlinear. This scale corresponds to the values of f_a through the relation

$$t = \frac{1}{2f_a} \text{ (given previously)}$$

The remainder of figure 8 is a repeat of the seat-response plot shown in figure 6(b) with the ordinate f_a common to both plots.

By means of figure 8 it is possible to explore the manner in which the maximum seat deceleration varies with the change in airplane velocity produced by the deceleration pulse. Assume that the performance of a seat designed for 10 g's in an airplane deceleration pulse whose amplitude A_a is 10 g's is to be determined. Assume also that the seat involved has a natural frequency of 8 cycles per second. With reference to the right side of figure 8, a half-sine airplane deceleration pulse of 10-g amplitude that produces a velocity change of 120 feet per second lasts for 0.6 second and has a frequency of about 0.8 cycle per second. The left side of the plot shows that a seat with a natural frequency of 8 cycles per second will have a normal response to a deceleration pulse of a frequency of 0.8 cycle. This means that that seat will experience a 10-g peak deceleration for which it is designed.

Now consider what happens in another airplane deceleration pulse whose amplitude A_a is also 10 g's, but whose time duration is only 0.12 second. The change in airplane velocity ΔV in this case is only 25 feet per second in contrast to the first case for which ΔV was 120 feet per second. The frequency of the airplane deceleration pulse f_a is now about 4 cycles per second. The seat with a natural frequency of 8 cycles per second would be operating in the zone of figure 8 where the peak seat deceleration is amplified, $A_s/A_a > 1$. For the airplane deceleration pulse that produced a ΔV of 25 feet per second, the seat would be overstressed. Yet, the previous case showed that it would serve without overstress in a deceleration pulse that produced a ΔV of 120 feet per second, the amplitude of the deceleration pulse being the same in both cases.

The reason for this seemingly anomalous result is related to the necessity for the seat to distort before the seat deceleration develops. Consider now the two airplane deceleration pulses of the same amplitude shown in figure 9. The pulse of short duration, which produces a relatively small change in airplane velocity, is shown in figure 9(a). Since the pulse has short duration, it rises quickly to its peak value. The seat deceleration develops more slowly because of the time required for the seat to distort. The undesirable velocity difference develops between the seat and the airplane that can produce a peak seat deceleration greater than the peak airplane deceleration. This condition corresponds to the deceleration pulse that produced a change in airplane speed of 25 feet per second.

The long-duration pulse that produces the large change in airplane velocity is shown in figure 9(b). The airplane deceleration rises gradually to its peak value because of the long pulse duration. For this reason, the seat has time to distort and develop its deceleration without appreciable lag. The seat deceleration can follow the airplane deceleration quite faithfully, and the velocity difference responsible for overshoot of the seat deceleration does not develop. These considerations emphasize the important role that the rate of rise of the airplane deceleration plays in determining the maximum seat deceleration.

Model of Deceleration Pulse for Seat Design

Since the rate of rise of the airplane deceleration proved to be an important quality, it is necessary to describe the airplane deceleration more accurately. The half-sine pulse used up to now has serious limitations. The model used for the deceleration pulse must include a description of the rate of rise as well as the magnitude and duration.

A proposed model for the airplane deceleration that approximates better actual deceleration measurements is shown in figure 10. The base deceleration pulse is divided into three time zones: a rise time during which the airplane deceleration grows to maximum value, a dwell during which the deceleration has a constant value, and a decay time taken equal to the rise time. It is recognized that there is no necessary relation between the rise and decay times. However, peak seat decelerations will most likely occur during the dwell. For this reason, the decay time is not as important as the rise time. Very little is lost by the convenience gained by equating the rise and decay times.

As before, secondary pulses are superimposed on the base pulse. The secondary pulse may vary considerably in shape. A half-sine pulse represents a reasonable approximation for the secondary pulses which are of short duration compared with the base pulse. Secondary pulses may appear anywhere on the base pulse and may attain peak magnitudes greater than that of the base pulse.

The importance of the dwell in the base pulse in determining maximum seat deceleration is illustrated schematically in figure 11(a). The base deceleration pulse is given by the curve ABDEF. Shown also is a half-sine pulse ABHJC having the same rise time and peak magnitude. The maximum seat decelerations obtained with each pulse, which differ only because of the dwell time, are compared.

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Consider first the seat response to the half-sine pulse. Assume that the situation shown in figure 9(a) applies; the seat deceleration lags the airplane deceleration appreciably. The seat deceleration develops along the curve AKJ (fig. 11(a)). The area between the half-sine airplane deceleration pulse and the seat deceleration curve, area 1, represents the relative velocity acquired by the seat. This velocity carries the seat deceleration beyond point J until area 2 between the seat deceleration curve and the airplane deceleration pulse is equal to area 1, in accordance with the earlier discussion. Maximum seat deceleration is attained at point L where the seat deceleration has about the same value as the peak airplane deceleration for the case shown.

The seat response to the long-duration airplane deceleration pulse ABDEF, which has the same rise time and peak magnitude as the half-sine pulse, develops initially along the line AK. Because the long-duration pulse maintains the peak deceleration beyond point B, the seat deceleration follows curve AKHD beyond point K. The seat velocity relative to the airplane grows continuously up to point D. After point D the seat deceleration continues to grow by virtue of this relative velocity and attains values greater than the airplane deceleration. The seat deceleration grows until area 3, between the seat deceleration curve and the airplane deceleration curve, is equal to that before point D (approximately equal to area 1). Since the airplane deceleration dwells at its maximum value, the seat deceleration must climb to point G in order to develop this area. This dwell is responsible for the seat deceleration attaining a maximum value at point G significantly greater than its value at point L in response to a half-sine pulse.

The ratio of maximum seat deceleration to maximum airplane deceleration for a base deceleration pulse having a dwell time appreciably longer than the rise time is given to a useful approximation in this problem in figure 11(b), taken from reference 1. The values for A_s/A_a in this figure are computed on the assumption that the rise-time portion of the airplane deceleration pulse has the cycloidal shape shown on the figure. In view of the variety of possible shapes for this curve that may actually appear in crash, further refinement in the definition of the rise-time curve is not justified. In figure 11(b), the term τ is the rise time and T is the period of the natural seat oscillation; the term T is related to the seat natural frequency through the expression

$$T = 1/f_n$$

According to figure 11(b) the peak seat deceleration can be equal to twice the peak airplane deceleration when the period of the seat natural oscillation is large compared to the rise time for the airplane deceleration. When the ratio of $\frac{\tau}{T}$ is greater than 2, the airplane and seat deceleration peaks are about the same. Since the ratio $\frac{\tau}{T}$ increases with seat stiffness for a given airplane deceleration rise time, stiff seats will give lower seat decelerations than flexible seats of low natural frequency.

ENERGY AVAILABLE FOR SEAT FAILURE

There remains one major area that requires discussion before the approach to seat design proposed in this report can be presented. This area treats the questions, "What is the energy available for breaking the seat, and how much is required?" While the treatment of these questions given here is admittedly approximate, the basic considerations involved are presented in their proper perspective and emphasis.

A case for which this treatment holds quite well is considered first. The airplane deceleration pulse has a broad dwell (fig. 12), and the seat deceleration lags the airplane deceleration to produce the overshoot shown in the figure. The velocity of the seat relative to the airplane acquired by the time the deceleration curves cross at point D commits the seat deceleration to grow to $A_{s,max}$. If the seat distortion x_{max} associated with $A_{s,max}$ is within the elastic limit of the seat, then the energy of seat deformation E_{max} is given by the expression

$$E_{max} = \frac{1}{2} kx_{max}^2 \tag{7}$$

This is the expression for the potential energy contained in an elastic system distorted an amount x_{max}.

It is important to note that the quantity E_{max} is predetermined by the time the seat-deceleration curve crosses the airplane deceleration curve at point D. At this point, the sum of the potential energy of seat distortion and the kinetic energy represented by the velocity of the seat relative to the airplane is equal to E_{max}. This is the energy available to stretch the seat to x_{max}. If the seat can distort elastically and absorb this energy, the seat does not suffer. However, if the elastic limit of the seat is exceeded before E_{max} is completely converted to potential energy of seat distortion, then a residue of energy is available to destroy the seat. This residue is equal to the difference between E_{max} and E_d, where E_d is the potential energy contained in the seat when distorted to its elastic limit x_d. Acordingly,

$$E = E_{max} - E_d = \frac{1}{2} k(x_{max}^2 - x_d^2) \tag{8a}$$

In order to put this equation into more convenient form, the following substitutions are made:

$$kx_{max} = MA_{s,max}$$

$$x_{max} = \frac{M}{k} A_{s,max}$$

$$kx_d = MA_{s,d}$$

$$x_d = \frac{M}{k} A_{s,d}$$

$$2\pi f_n = \sqrt{\frac{k}{M/32}}$$

$$k = \frac{(2\pi f_n)^2 M}{32}$$

$$F_d = kx_d$$

$$E = \frac{1}{2} \frac{k^2 x_d^2}{k} \left(\frac{x_{max}^2}{x_d^2} - 1\right) = \frac{1}{2} \frac{F_d^2}{(2\pi f_n)^2 \frac{M}{32}} \left[\left(\frac{A_{s,max}}{A_{s,d}}\right)^2 - 1\right] \tag{8b}$$

This function is plotted in figure 13, with the energy given in foot-pounds, the seat design strength F_d in pounds force, and the passenger mass M equal to 200 pounds mass.

Equation (8b) is quite accurate as long as the design strength of the seat $A_{s,d}$ is greater than the magnitude of the airplane deceleration pulse. However, if $A_{s,d}$ is less than the value of the airplane deceleration, then the seat acquires a velocity relative to the airplane which differs from that implied by equations (8a) and (8b). If the stiffness of the seat declines after the elastic limit is exceeded, then the seat will acquire a higher velocity than it would if the stiffness were maintained. This higher velocity is related to the time lag involved in the development of the seat deceleration force associated with seat distortion discussed earlier. The higher velocity acquired by the seat increases the energy available for destroying it. If the seat stiffness increases after the elastic limit is exceeded, then the velocity of the seat relative to the airplane is less than it would be if the original stiffness were maintained. The energy available to destroy the seat is reduced below that given by equations (8a) and (8b). However, these equations give a good approximation to the energy available to destroy the seat in any case, and can serve the seat designer with an index of the direction his design should take.

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Relation of Seat Destruction Energy to Seat Design

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It is appropriate now to point out briefly what this seat-destruction energy does to the seat. This is done with reference to figure 14, which shows a stress-strain curve for the seat similar to figure 3 carried beyond the elastic limit. Seat destruction is viewed here as a progressive process that begins when the elastic limit is exceeded. The seat-destruction energy is available to stress the seat beyond the elastic limit. The energy absorbed in seat deformation beyond the elastic limit is equal to the area under the stress-strain curve beyond the elastic limit indicated by the shaded area in figure 14(a).

A desirable seat is one which maintains a high value of holding force F as it stretches beyond the elastic limit. The seat should be capable of appreciable deformation beyond the elastic limit with high holding force maintained to the breaking point as shown in figure 14(a). Seat failure will not occur if the seat-breaking energy E can be absorbed in seat deformation beyond the elastic limit before the breaking point is reached. This condition is illustrated in figure 14(a).

Two undesirable seat-deformation modes beyond the elastic limit are shown in figure 14(b). Curve A shows high seat-holding force beyond the elastic limit, but a small allowable deformation before breaking. Such a curve would be obtained with a seat whose members being deformed are brittle, or one in which the entire seat load passes through a single structural element which is the weak link in the stress chain. Curve B shows a seat-holding force that declines rapidly with deformation beyond the elastic limit. Highly efficient, lightweight, seat structures may have this quality. Modest changes in the shapes of the members of these seats sometimes result in the rapid deterioration in holding force illustrated by curve B.

PROPOSED APPROACH TO SEAT DESIGN

The three principal qualities of a seat that relate to its ability to hold a passenger through a deceleration pulse are the seat natural frequency, its static strength, and its ability to absorb energy in deformation beyond the elastic limit. The problem now is to determine a set of magnitudes for these qualities that will produce a seat that will serve for a deceleration pulse of given description. Presumably, this deceleration pulse is the design requirement for the seat.

Design Values of Airplane Deceleration Pulses

A study of the airplane deceleration records obtained during the crash-research program suggests the description of crash deceleration pulses shown in table I. The severity of the crash pulse is indicated by the approximate airplane velocity change produced by the pulse. The pulse is made up of a base pulse and a secondary pulse of the type shown in figure 10. A variety of pulses can occur in a crash to produce a given airplane velocity change. The values of the pulse components given in table I are considered to be quite severe from the standpoint of the seat, and yet are consistent with crash measurements. Some of the values given are taken directly from crash data. Others are obtained from a study of the trends shown by a substantial quantity of information obtained during the crash program. This is particularly true for the more severe crash pulses.

The deceleration pulses listed in table I are grouped under transport and cargo headings. The transport category includes the modern pressurized low-wing or middle-wing airplane. The cargo category applies to the high-wing unpressurized airplane such as the C-82 packet from which some of the data given in the table were obtained. A cargo airplane of this type is shown in the table to have lower maximum deceleration than the transport. This difference results from the fact that the belly structure of this cargo type is too soft to dig deeply into the ground on crash. The airplane deceleration produced by ground-plowing and tearing of the soft belly structure reaches modest values therefore.

The strong belly of the pressurized transport will dig more deeply into the ground upon crash. Exposed members of the airplane structure that engage the ground are stronger than those of the cargo airplane considered here. Larger loads between these members and the ground can develop before failure of these members occurs.

Because of the greater stiffness of the transport structure, it will rebound after impact and disengage from heavy ground contact more rapidly than the cargo airplane. The major deceleration pulses will be of shorter duration for the transport than for the cargo airplane.

Most airplanes have structures which lie between the two types given. Some judgment is required to determine how to modify the values given in table I to apply to a given airplane. Little error will be made if the deceleration pulses listed for the transport are taken to apply to all low-wing and middle-wing pressurized transport and cargo airplanes. Unpressurized high-wing transport and cargo airplanes can use the deceleration pulses listed for the cargo airplane.

The choice of deceleration pulse which seats are to meet depends on many factors, including seat weight and comfort. All the deceleration pulses given in table I can be survived if a suitable seat is provided.

The values given in table I describe deceleration pulses acting in a longitudinal direction from front to rear. Lateral and rearward decelerations can be assumed to have magnitudes equal to 75 and 50 percent, respectively, of those shown in the table with the same time durations. The change in airplane velocity over these lateral and rearward pulses would be reduced correspondingly. The deceleration in the vertical direction can be taken to be the same as those shown in table I.

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Basis of Proposed Approach

The proposed approach to seat design is based on equation (8b) in which the three principal seat qualities appear together. By means of equation (8b) a consistent set of values of the principal seat qualities are defined. In making use of equation (8b) it is assumed that the seat designer knows approximately how the seat strength and stiffness are related for the type of seat he makes.

Evaluation of Maximum Seat Deceleration

The maximum seat deceleration $A_{s,max}$ is a key parameter in equation (8b). Its evaluation as a function of the seat natural frequency f_n is required. To do this the deceleration pulse for which the seat is designed to withstand is chosen. Assume that the deceleration pulse is the one given in table I for a transport airplane velocity change of 80 feet per second. Assume further that, for the moderate degree of accuracy required in calculations of this type, the seat deceleration may be computed separately for the primary and secondary pulse components with due regard for the phase relation involved. Seat response to the complete pulse is made up of the sum of the responses to the separate components. This implies that the seat represents a linear elastic system. Since attention is focused on the seat as its first distortion grows monotonically to a maximum, the assumption of linearity applies reasonably well. For reasons discussed later, the seat departs markedly from a linear elastic system in its oscillation following this first displacement to maximum distortion. However, friction and other damping of the seat oscillation are considered to make the seat displacement subsequent to the first peak of lesser importance.

A method for obtaining the maximum seat deceleration for the half-sine secondary deceleration pulse is discussed previously in this report. This method makes use of the plot shown in figure 6(b), which is reproduced in more complete form in the upper half of figure 15(a). As before, the frequency of the deceleration pulse (secondary half-sine pulse) f_a is plotted as the ordinate and the natural frequency of the seat f_n as the abscissa. The family of straight lines represents combinations of f_a and f_n for which the ratio of maximum seat deceleration to maximum airplane deceleration have the values assigned to the lines. The duration of the half-sine pulse is given from table I as 0.03 second. This corresponds to a full-wave frequency of 17 cycles per second for the case used in this example. The designer can use figure 15(a) to obtain the ratio of maximum seat to maximum airplane deceleration by drawing a horizontal line representing f_a equal to 17 cycles per second as shown in the figure. Each intersection of this horizontal line with lines of constant A_s/A_a determines a ratio of maximum seat to maximum airplane deceleration for the corresponding value of the seat natural frequency f_n shown on the abscissa. Since the magnitude of the secondary pulse A_a is given in table I, it is possible to plot A_s in response to this secondary pulse as a function of f_n from the information given in the chart. This plot is given in the lower half of figure 15(a), where the lower ordinate is $A_{s,max}$. Notice that the seat response to the secondary half-sine pulse increases with seat natural frequency. For this secondary pulse the lower seat natural frequencies would be preferred.

A similar plot can be made for the seat response to the base airplane deceleration pulse as a function of seat natural frequency based on the information provided in figure 11(b). This plot provides the second curve on the lower part of figure 15(a). For this base pulse the maximum seat deceleration increases with decreasing values of seat natural frequency in contrast to the trend for the secondary pulse.

The secondary pulse can occur anywhere on the base pulse. It is reasonable to assume that the maximum seat deceleration in response to the secondary and base pulses will occur at the same time often enough to consider this to be the design condition for the seat. The total seat deceleration is obtained by simply adding the maximum seat response to the secondary and base pulses. The third curve in the lower half of figure 15(a) results. This curve shows that the maximum seat deceleration $A_{s,max}$ changes little with natural frequency of the seat for the design conditions chosen. Over the frequency range the maximum seat deceleration varies between 40 and 48 g's in response to a peak airplane deceleration of 33 g's, being the sum of the magnitudes of the primary and secondary pulse.

The designer's estimate of the variation of seat natural frequency with seat strength provides the remaining information required for equation (8b). Assume that the variation of seat strength with seat natural frequency for the seat type involved has the form shown at the top of figure 15(b). This is a purely hypothetical relation. It is used in this report solely for the purpose of illustrating the method under discussion. In this figure, seat strength is given in terms of force F_d or acceleration $A_{s,d}$. Both forms of expressing seat strength can be used in equation (8b).

Since all the quantities required for equation (8b) are given directly in terms of the seat natural frequency f_n, it is possible to plot the seat destruction energy E as a function of f_n. This is done in the lower half of figure 15(b) by means of the information given in figures 15(a) and (b). The upper and lower curves of figure 15(b) show the combination of seat natural frequency, strength, and energy absorption in deformation beyond the elastic limit that are required of a seat to serve in the airplane deceleration pulse chosen here as the basis for the design. All these properties can be obtained from measurements made under static conditions. This method of relating the properties of a seat measured under static conditions to its ability to serve under the dynamic conditions of a deceleration pulse constitutes a principal objective of this report.

According to the results obtained in figure 15(b), the seat destruction energy to be absorbed E decreases with increasing seat strength. A seat with a design strength of 20 g's would have to absorb about 3000 foot-pounds before failure if it is to serve this 33-g peak airplane deceleration. A seat designed for 28 g's would have to absorb about 900 foot-pounds. This would mean a seat deformation of 0.16 foot beyond the elastic limit for the seat if it maintained its design holding force F_d of 5600 pounds over this deformation. If this energy absorption beyond the elastic limit is provided before the seat breaks, then this 28-g seat would serve in this airplane deceleration that reaches a peak of 33 g's and subjects the passenger to a maximum deceleration of about 48 g's. The seat natural frequency would be $11\frac{1}{2}$ cycles per second.

The two curves of figure 15(b) provide the designer with matched sets of values for the seat parameter that will serve the design airplane deceleration pulse. The common tie between these curves is the seat natural frequency f_n. Obviously, it will be impossible to provide the large energy absorption E required for the relatively low-strength seats indicated in figure 15(b). This requirement limits the choice of seat parameter sets to those which include values of E that can be realized in practice.

It is conceivable that special arrangements can be made in the seat to provide for extra seat deformation beyond the elastic limit before the seat breaks. The amount of intentional deformation that may be permitted is limited by the space between adjacent seats. In transport airplanes about 1 foot of fore-aft displacement is available to exploit in this way.

Considerations of seat weight and comfort will further limit the choice of seat parameter sets. When seats are designed to hold passengers in deceleration that approaches human tolerance, the seat natural frequency that keeps the passenger deceleration within the tolerance limit has obvious merit. In the example given previously, there was little to gain from a choice of seat natural frequency. However, for airplane deceleration pulses where the secondary pulse is larger in magnitude than the base pulse some advantage may appear in favor of lower seat frequencies.

EXPERIMENTAL SEAT STUDIES

The key role played by seat natural frequency in determining the maximum seat deceleration suggested a class of seat that exploits this parameter to reduce the seat deceleration. This seat makes use of the fact that the seat deceleration in response to the base airplane deceleration pulse decreases with increasing seat natural frequency as shown in figures 11(b) and 15(a). Seat deceleration in response to the short-duration secondary pulse decreases with decreasing seat natural frequency, as shown in figure 15(a). A seat that has both a high- and low-frequency range was constructed to determine if some gains in passenger deceleration reduction can be achieved in this way. The seat was tried in the laboratory and in some of the airplane crashes conducted in this program.

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Description of Experimental Seat

Several forms of the seat were made which employed two ranges of natural frequency. The stress-strain curve for these seats had the general character shown in figure 16. The seat has large stiffness and, consequently, high frequency for a holding force up to several thousand pounds. The high-frequency range corresponds to the force-distortion line of large slope shown in figure 16. Beyond that value of holding force the seat stiffness is reduced considerably as indicated by the marked reduction in slope of the force-distortion line in figure 16. For this range, the seat has a low natural frequency. Because of this dual frequency range the seat will be called a duplex seat.

A seat with this dual frequency range in principle would respond to an airplane deceleration pulse in the manner shown in figure 17. Because of the large stiffness of the seat under low load, the seat deceleration grows rapidly with displacement and follows the early portion of the airplane deceleration pulse quite faithfully. A large difference in velocity between seat and airplane is avoided in this way and a marked overshoot of seat deceleration does not occur. Also, when high short-duration secondary pulses are encountered, the seat will distort into its low-frequency range and provide some attenuation of the secondary pulse deceleration.

A variety of seats were made having elastic properties of the same general character as that shown in figure 16. There were considerable differences among the seats in the stiffness in both the low- and high-frequency ranges. However, all the seats had the general form shown in figure 18. The seat pedestal was made in two parts. One part is a cylindrical floor piece that is fixed to the fuselage floor, and the other part is similarly shaped but fixed to the seat pan. The two parts of the pedestal are joined by an elastic band that is prestressed to force them together. For a seat having the stiffness characteristic shown in figure 16, this prestress force requires that a force of 2400 pounds be applied to the seat belt or seat back to begin to stretch the elastic band. Seat distortion under loads less than 2400 pounds takes place through the seat structure above the pedestal. The seat operates then on the high-stiffness portion of the curve. When this load exceeds 2400 pounds, the elastic band stretches and the seat distortion follows the low-stiffness portion of the curve of figure 16.

Seat parts above the pedestal are made of air-inflated rubberized fabric. These air-inflated members are reinforced with lightened aluminum structural elements. These elements are shielded from the passenger and others in adjacent seats by the air-inflated members. The seat maintains its shape and strength if the air is lost from the inflated members. Because the seat pedestal is cylindrical, it can distort under load in a horizontal plane, regardless of the direction of the load.

Deceleration Pulse Loads with Experimental Seats

Longitudinal loads. - The effect of deceleration pulse loads on experimental seats was studied early in this work to determine whether the advantage of the double seat natural frequency range just described is actually realized. By means of the apparatus shown schematically in figure 19, a single deceleration pulse was imposed on a seat of this type carrying a 200-pound dummy as passenger. The seat was mounted on a platform representing the fuselage floor. The platform was suspended by cable from a high support to form a swing. The dummy passenger, seat, and swing platform were suitably fitted with accelerometers, which provided a continuous deceleration record. The swing deceleration pulse was produced by displacing it about 12 feet above its rest level and releasing it to strike the target on wheels shown in figure 19. A typical swing deceleration pulse appears as the lowest curve on figure 20. The swing deceleration pulse reached a peak of about 30 g's. The deceleration endured for only 0.04 second because of the low velocity of the swing upon impact with the target.

The dummy, riding rearward in the duplex seat, experienced a peak longitudinal hip deceleration of 20 g's and a longitudinal chest deceleration of 12 g's, as compared with a peak swing deceleration of 30 g's. In a rearward-facing seat of this type, which pivots under load from a point under the passenger, the hips will decelerate more rapidly than the chest. This results from the fact that the chest and hips travel at the same speed before the swing decelerates upon impact with the target. Because the hips lie closer to the point of flexure of the pedestal than does the chest, the hips are subject to a higher deceleration. The mechanical reasons for this are beyond the scope of this paper. Since human vital organs lie close to the chest this effect constitutes an advantage.

The seat used to obtain the data shown in figure 20 had a low prestress in the elastic band joining the upper and lower halves of the seat pedestal. The large time lag between the rise of swing deceleration and that of the dummy's hips shows that while this seat serves well for a short-duration pulse it is unsuited for the long-duration base pulse described in the previous section of the report. The swing deceleration in figure 20 has the character of a secondary pulse for which the low frequency of the seat has the distinct advantage shown by the data of figure 20.

A rigid seat of conventional design mounted rearward on the same swing produced the data shown in figure 21. The swing was dropped from a lower elevation than was the case for the data of figure 20. The swing deceleration now peaks at 22 g's. The dummy's hips and chest reached peak decelerations of 27 and 30 g's, respectively, showing the amplification of the airplane deceleration covered earlier in this discussion. This increase in dummy's deceleration over that of the swing is in marked contrast to the decrease recorded for the duplex seat shown in figure 20.

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Vertical loads. - Vertical crash decelerations can be as large as those in the longitudinal direction. Devices for reducing the vertical blow felt by the passenger by permitting vertical seat distortion are limited to a distortion of about 8 inches, which represents the free space between the seat pan and the floor. Further, the vertical seat deformation should be provided in such a way that the seat strength in other directions is not reduced when this deformation occurs.

Elastic devices for giving the seat a natural frequency in the vertical direction could be designed according to the principles discussed earlier. However, since the chances are that high vertical decelerations will appear only once in a crash, elaborate arrangements for accommodating the vertical deceleration are not justified.

The simplest devices for this service are designed to deform under the vertical load after it attains values approaching human tolerance limits of about 20 g's. The most useful force-deformation relation is illustrated in figure 22(a). This curve shows that the vertical force exerted by the passenger on the device holds constant at a high tolerable value as the device deforms. In this way the maximum vertical energy absorption is attained within human tolerance.

One of the many possible devices for this service is shown in figure 22(b). The device consists of three concentric cylinders made of corrugated sheet aluminum. Under a load of 20 g's with a 200-pound passenger the bellows-like cylinders collapse inelastically.

Swing studies of the effectiveness of these cylinders were conducted with the seat mounted with its back parallel to the floor of the swing. With this seat orientation the swing deceleration acts through the seat in a direction parallel to the spine of the dummy whose torso is horizontal in this experiment. The data of figure 23 show that, whereas the swing decelerations reach a peak of 40 g's, the deceleration of the dummy's hips leveled off at the design 20 g's.

Seat performance in crash. - In crash study of seat performance both rigid and experimental duplex seats with high prestress were used. In one crash of particular interest a high lateral and vertical deceleration was developed. A lateral load is one parallel to the fuselage floor and perpendicular to the long axis of the fuselage.

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The lateral airplane deceleration is shown in figure 24 along with the hip and chest decelerations of dummies in rearward-facing rigid and duplex seats. Because the pedestal of the duplex seat is cylindrical it can also distort elastically in the lateral direction. The lateral airplane deceleration reached a peak value of 22 g's in one direction and 10 g's in the opposite direction. The hips of the dummy in the rigid seat range between 30 g's in both directions, while for the dummy in the duplex seat the hip decelerations lie between 30 and 12 g's. A comparable advantage appears for the duplex seat for the chest decelerations.

Unfortunately, the instrumentation for the longitudinal declerations was destroyed in the crash and no comparison can be made.

The decelerations measured in the vertical direction in the same crash are given in figure 25. The duplex seat was equipped with the corrugated cylinders for absorbing the vertical blow. The vertical airplane deceleration peaked at 77 g's. The seat pan of the rigid seat failed in a downward direction after recording a deceleration of 45 g's. When this failure occurred, the dummy's chest showed a momentary deceleration of about 52 g's. The corrugated cylinders in the seat of the duplex flexible seat held the vertical deceleration of the dummy's hips to 30 g's and the chest to 22 g's. The high lateral deceleration that accompanied this vertical deceleration caused nonuniform loading of the concentric cylinders. The resulting unsymmetrical modification of cylinders, shown in figure 26 caused them to stiffen as they deformed. The higher-than-design deceleration of 30 g's is attributed to this effect. No doubt a more suitable device of this type would avoid this effect.

A photograph of the rigid seat after crash is given in figure 27. Failure of the seat pan and a diagonal brace is evident. Failure of this diagonal brace following seat-pan failure reduced the seat strength in a horizontal plane. Failure of welds joining the tubular members of the seat pedestal which followed the loss of the diagonal brace are difficult to make out in the photograph.

When devices are used to reduce the vertical blow, the seat should not lose its ability to withstand a blow in a horizontal direction when the vertical blow is absorbed. This principle was observed in the use of the corrugated cylinder with the duplex seat shown in figure 26. Collapse of the corrugated cylinder had no effect on the strength of the remainder of the seat.

CONCLUDING REMARKS

The discussion so far has dwelt on the ability of a seat to support a passenger through a deceleration pulse. No attempt was made to describe

the passenger's motion beyond the first deceleration peak he experiences. Formal mathematical solution of the equations of motion of the passenger in a seat having the elastic properties assumed here shows the passenger in oscillations through many peaks. These oscillations are what one would expect of a simple elastic system of the type assumed for the seat and passenger. In an actual seat there is some effective frictional 4150
damping in the system that rapidly dampens the passenger motion. Passenger deceleration peaks after the first are of lower magnitude and sometimes do not occur at all. Motion pictures of the dummy passenger motion and deceleration measurements taken during crash with instrumented dummies support this point.

Damping action in the seat-passenger system arises from friction between seat structural elements that bear on each other and move when the seat distorts under load, from high friction force between the passenger and the seat as he slides within the limits applied by the belt, and from the flexure of the passenger over his seat belt. Some of the rebound kinetic energy of a passenger in a rearward-facing seat is dissipated in downward flexure over the seat belt that compresses the passenger against his thighs. This energy is no longer available to drive the oscillating system, and the amplitude of the deceleration peaks subsides. In the duplex seat shown in figure 18 the upper and lower sections of the seat pedestal are separated by a rubber mat. Friction work is produced by the relative motion of the pedestal sections bearing with large force on this rubber mat. This force is produced by the high prestress exerted by the elastic band joining the two halves of the pedestal.

The effect of slack between the passenger and the seat was also omitted from the analysis given earlier. For a rearward-facing passenger this slack is provided in part by the gap between the lower back of the passenger and the seat back. Most people sit with the upper back in contact with the seat, but with the lower back up to 4 inches away. The lower, massive portion of the body must move through this distance before it contacts the seat back. Also, the seat-back cushioning must be compressed by the passenger before the main structure of the back feels the passenger load. For the forward-facing passenger the seat slack appears when the seat belt is worn loosely, when it slips in the buckle, and if it stretches under load.

The time required to displace the passenger until he comes into substantial contact with the seat main structure permits the passenger to acquire velocity with respect to his seat. This undesirable relative velocity increases the magnitude of the peak seat deceleration over that which is obtained in the absence of slack.

Some appreciation for the marked increase in seat deceleration provided by the slack can be obtained from the computed data of figure 28. Whereas the maximum seat deceleration when no slack is present never exceeds twice that of the airplane, the data of figure 28 show this ratio to increase well beyond this value. When slack is present the ratio of seat to airplane deceleration increases with seat natural frequency. This ratio attains a value of $3\frac{1}{2}$ when the seat natural frequency is 17 cycles per second with an effective seat slack of 3 inches.

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For a rearward-facing seat the cushioning provided for comfort is in conflict with the ability of the seat to hold in a crash. Some compromise between comfort provided by this cushioning and safety may be required in the design of aft-facing seats. Likewise, seat belts that slip or stretch under low-load are to be avoided, particularly in forward-facing seats.

Deep seat-pan cushions introduce the same objectionable slack in a vertical direction. The use of extra seat cushioning, sometimes practiced in fighter aircraft, increases the danger of back injuries in a vertical deceleration pulse. A proper seat-pan cushion should compress completely under the weight of the occupant and bring his buttocks in substantial contact with the seat pan. The illusion of greater protection provided by deep cushioning comes from sensations of comfort experienced when forces equal to the weight of the occupant are exerted. When these forces grow to 10 and 20 times the occupant's weight in a deceleration pulse, the protection afforded by the deep cushion no longer exists. Instead, the detrimental effects of slack appear as the occupant compresses the cushion and acquires velocity with respect to the seat pan he will ultimately strike.

Methods of fastening seats to the airplane should be subject to a critical engineering study. Current practice of fastening the seat to the airplane fuselage wall and the floor exposes the seat to possible failure when the airplane structure between the fastening points distorts in crash and shortens the distance between them. Even unoccupied seats may be lost when this happens.

Seat fastenings must be able to support the seat design load and must engage airplane structure that will not flex or break under this load. Floor structure that flexes can seriously modify the effective seat natural frequency and reduce the ability of the seat to support the passenger.

The higher landing and takeoff speeds of airplanes like the jet transport increase the probability that more than one principal declaration pulse will be experienced in a crash. For this reason the seat designer should consider the residual strength of a seat following a crash deceleration pulse for which the seat is designed. The higher the landing speed of the airplane, the higher this residual strength should be. A proposed description of the second deceleration is shown in table I for airplanes having a landing speed of 180 feet per second. The residual stiffness should be high enough to serve in a second deceleration whose primary and secondary pulse amplitudes have the values shown in the appropriate columns. The pulse durations and rise times should be the same for the first and second decelerations. For the case where ΔV is equal to 180 feet per second in the first deceleration, no second deceleration will occur since the airplane has come to rest.

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Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 25, 1956

REFERENCE

1. Anon.: A Comparative Study of Pulse and Step-Type Loads on a Simple Vibratory System. Tech. Rep. No. 16, Structural Dynamics, Vibration Res. Lab., School of Eng., Stanford Univ., Jan. 25, 1952. (Navy Contract N6-ori-154, Task Order 1 (NR-035-033).)

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TABLE I. - DESIGN VALUES OF LONGITUDINAL

AIRPLANE DECELERATION PULSES

First deceleration								
	Transport				Cargo			
Δ V	50	80	130	180	50	80	130	180
Primary								
Maximum g's	12	18	20	20	5	8	10	10
Pulse duration, sec	0.20	0.20	0.25	0.30	0.50	0.38	0.46	0.58
Rise time, sec	Sine	0.06	0.045	0.03	Sine	0.10	0.08	0.06
Secondary								
Maximum g's	10	15	20	25	7	10	12	15
Pulse duration, sec	0.02	0.03	0.04	0.03	0.06	0.04	0.04	0.03
Second deceleration								
Primary pulse, g's	9	9	7	1	4	4	3	1
Secondary pulse, g's	8	7	7	1	6	5	4	1

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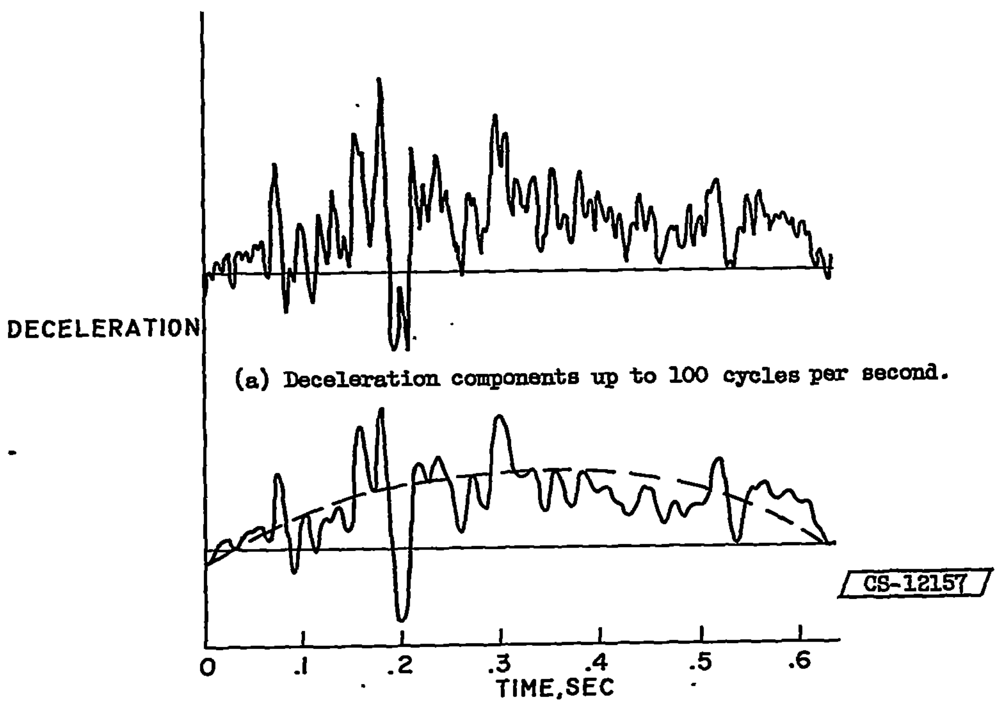
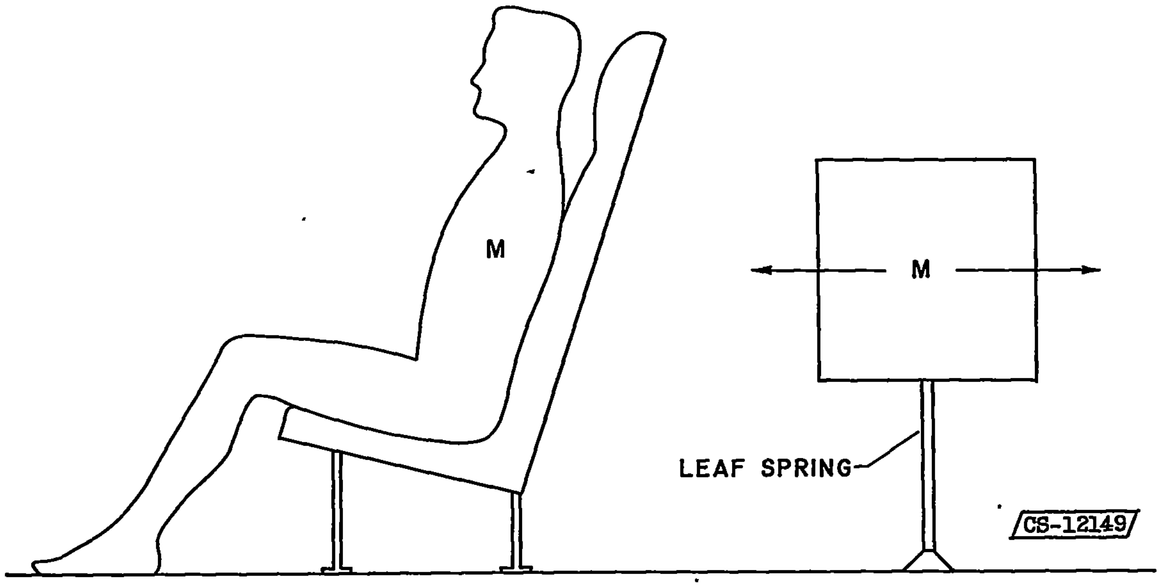


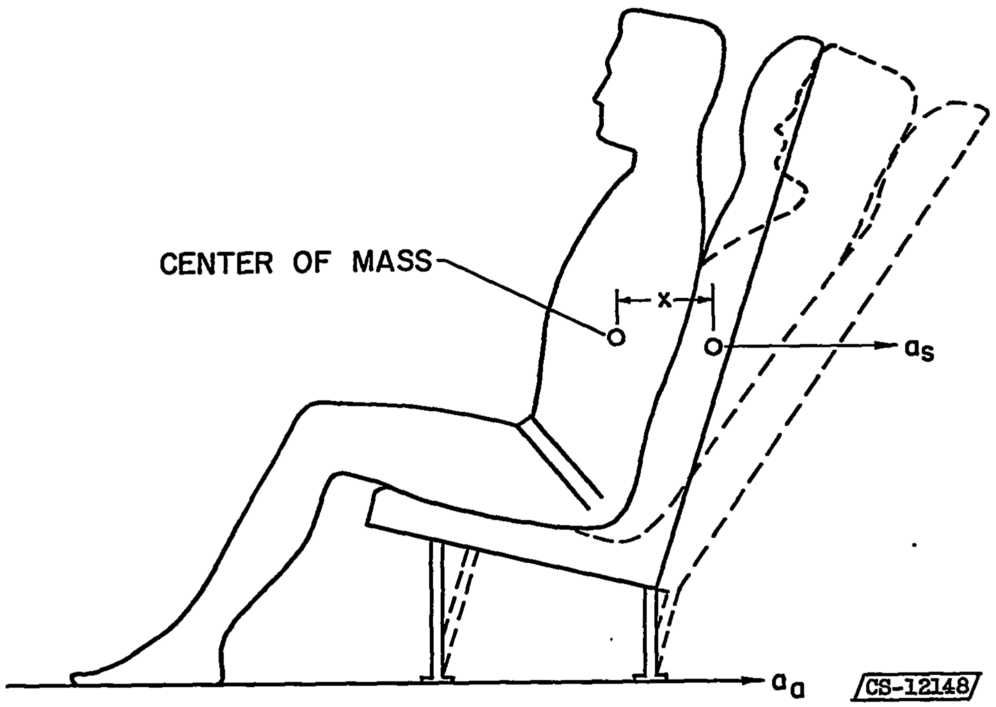
(a) Deceleration components up to 100 cycles per second.

(b) Deceleration components up to 50 cycles per second.

Figure 1. - Fuselage floor deceleration, longitudinal.



(a) Mass-spring system.



(b) Seat distortion.

Figure 2. - Schematic model of airplane seat.

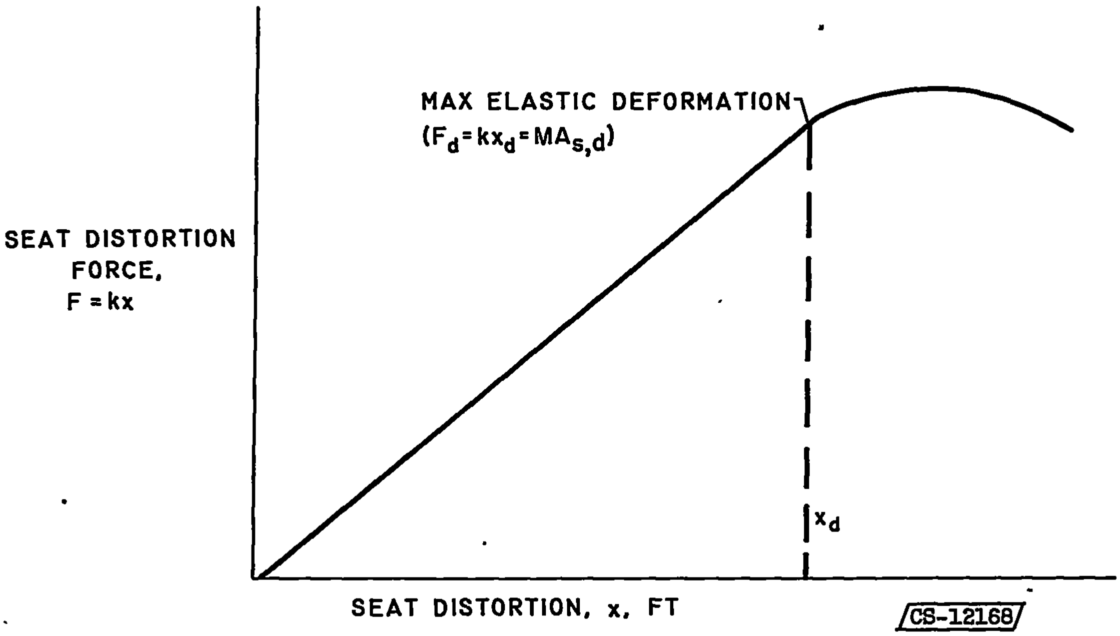


Figure 3. - Seat elasticity.

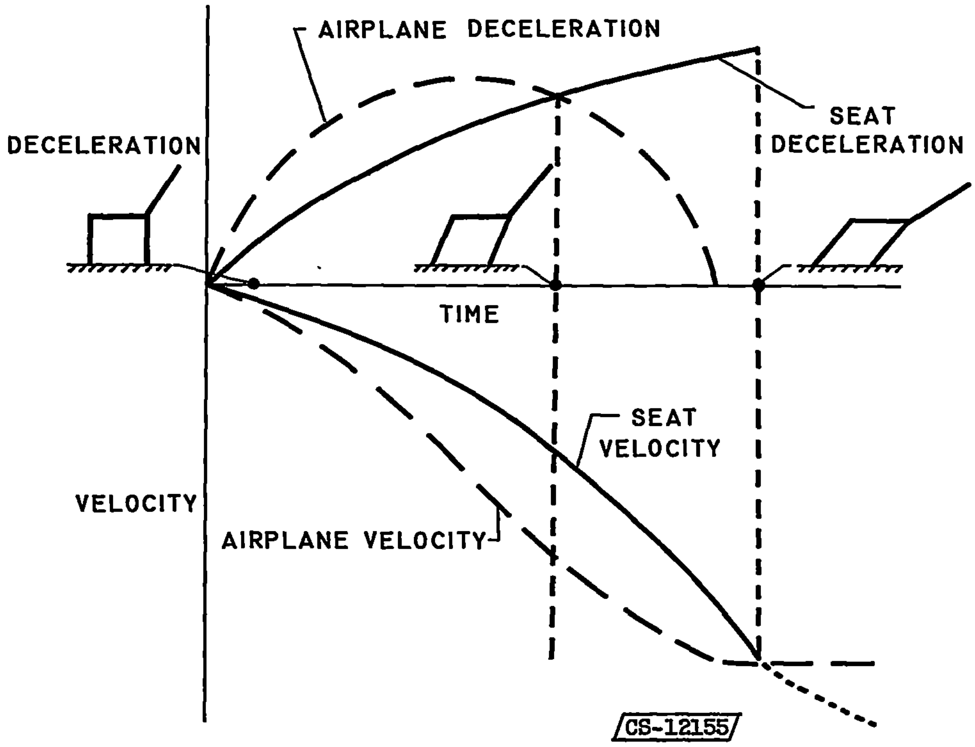


Figure 4. - Relative seat and airplane deceleration and velocity.

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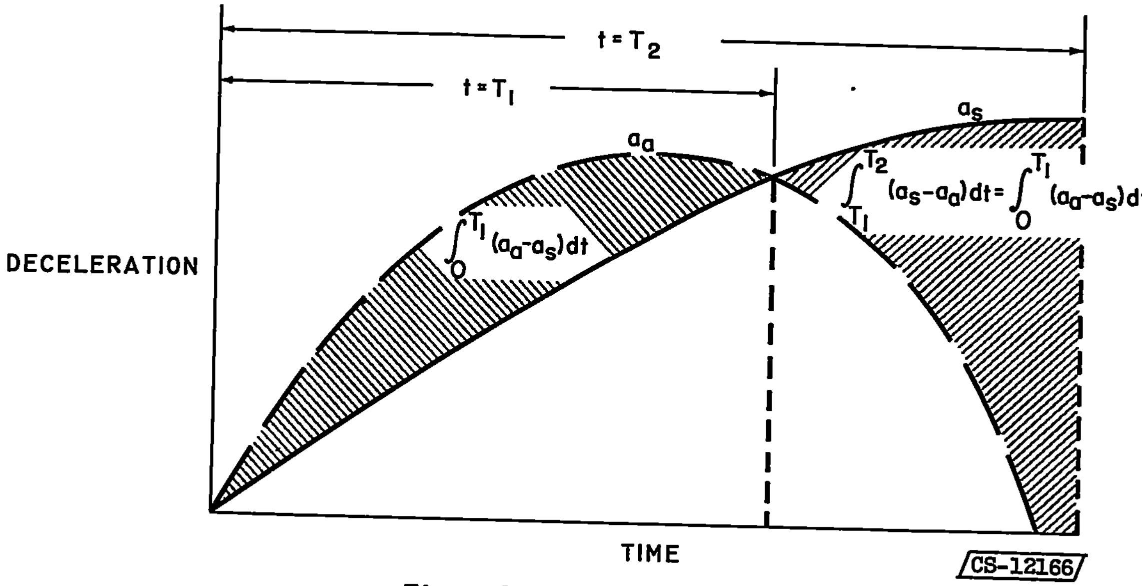
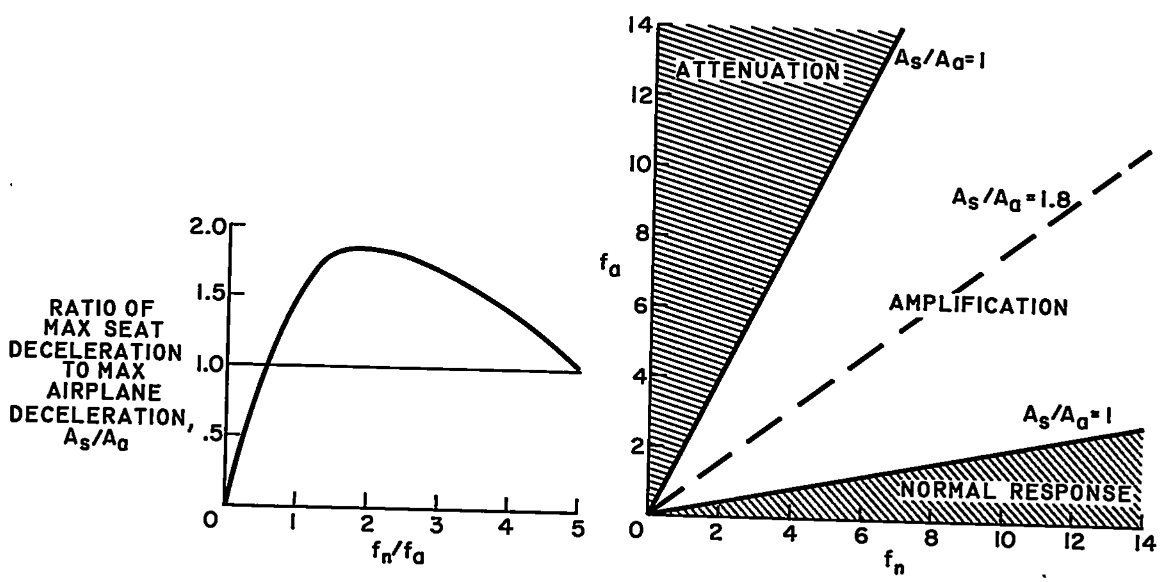


Figure 5. - Seat deceleration response.



(a) Ratio of maximum seat to maximum airplane decelerations against frequency ratio.

(b) Replot of (a) in terms of airplane and seat frequencies.

Figure 6. - Ratio of seat to airplane deceleration.

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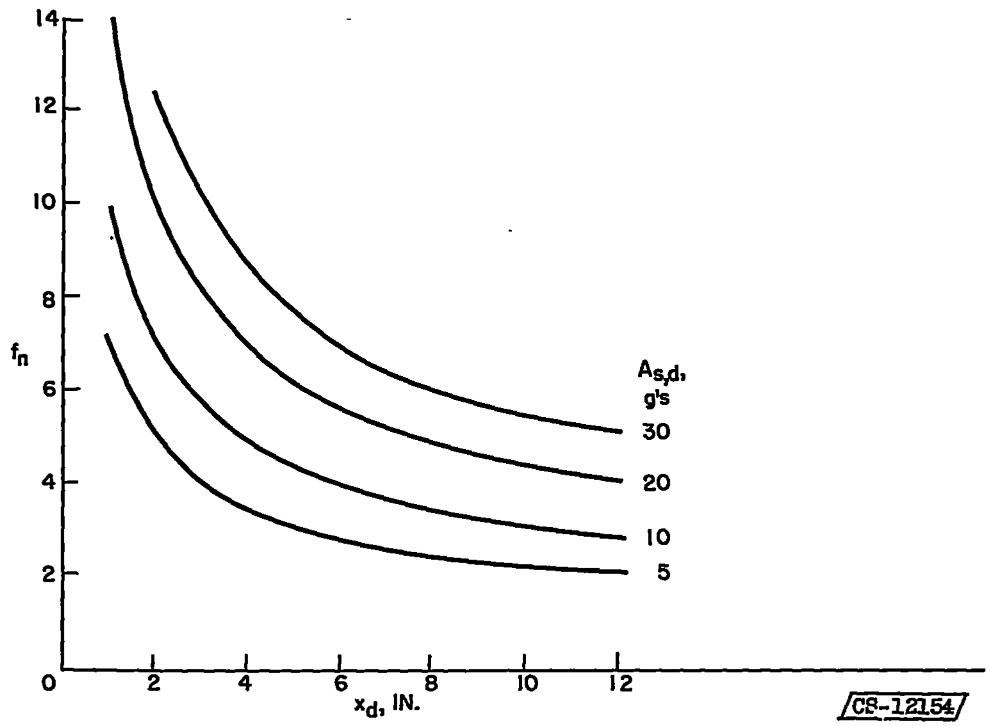

Figure 7. - Variation of seat natural frequency with design distortion.

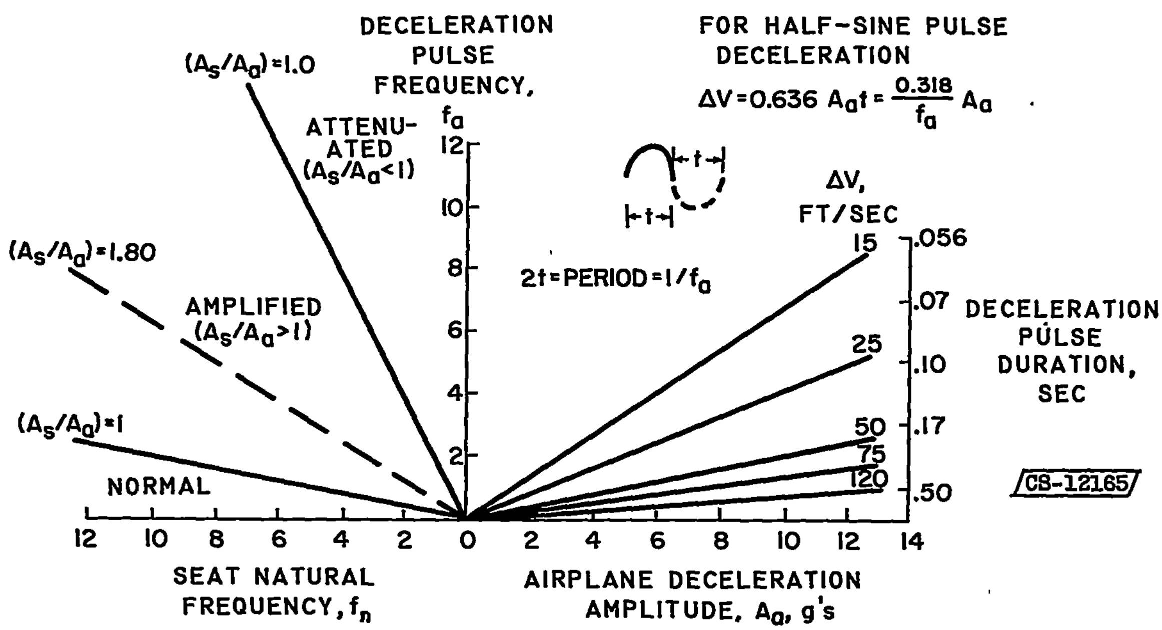

Figure 8. - Seat response, half-sine pulse.

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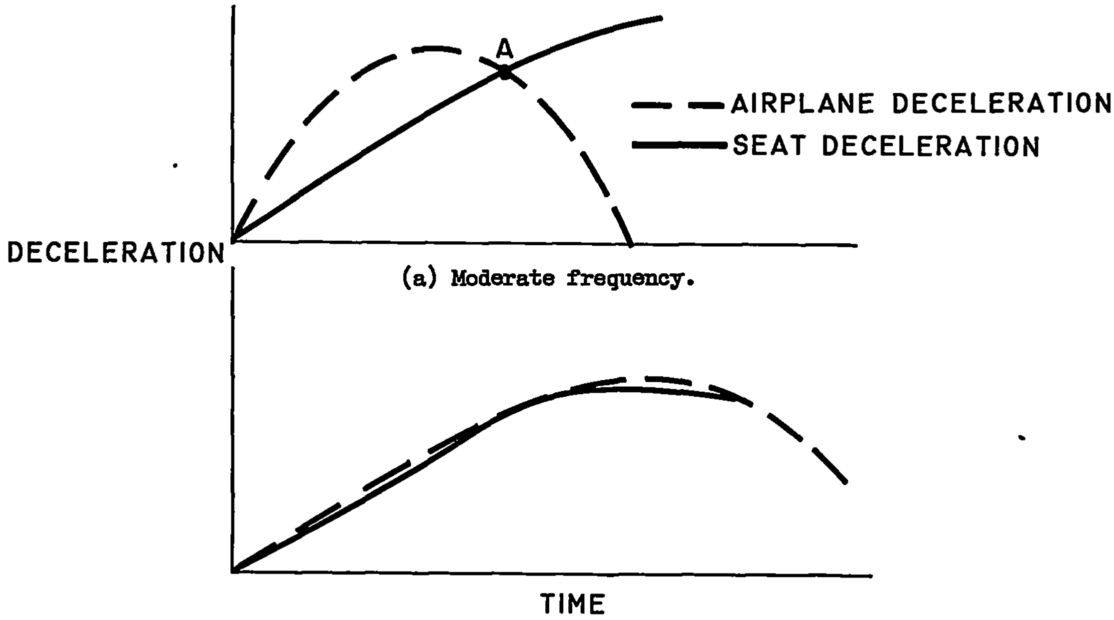

(a) Moderate frequency.

(b) Low frequency.

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Figure 9. - Effect of airplane deceleration frequency on seat deceleration.

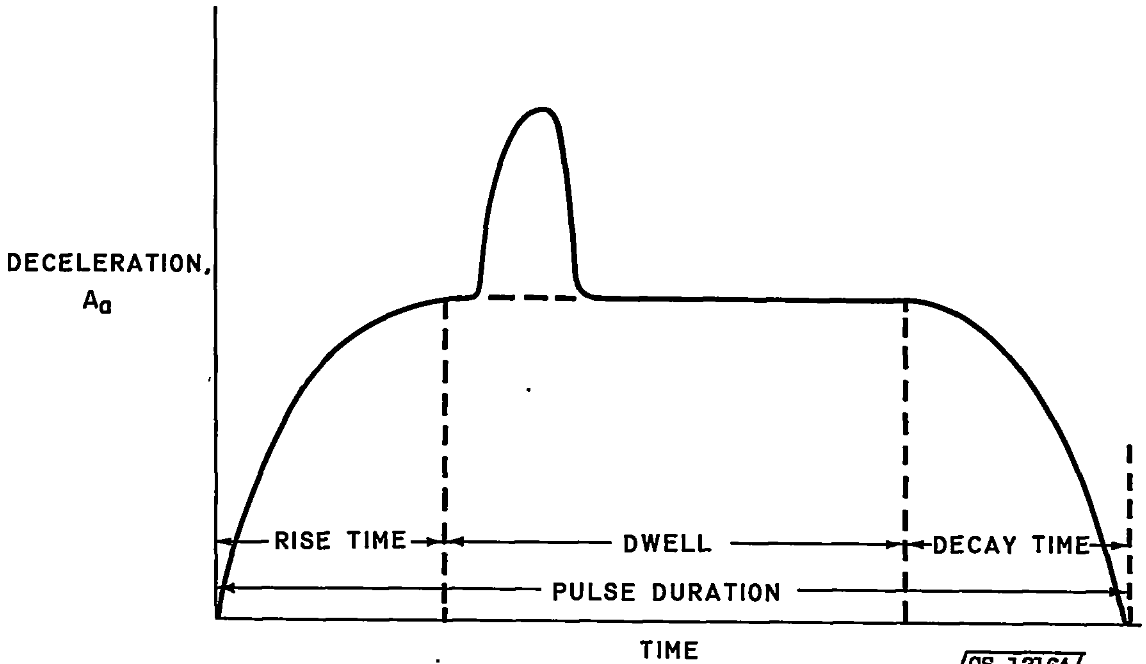

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Figure 10. - Deceleration pulse components.

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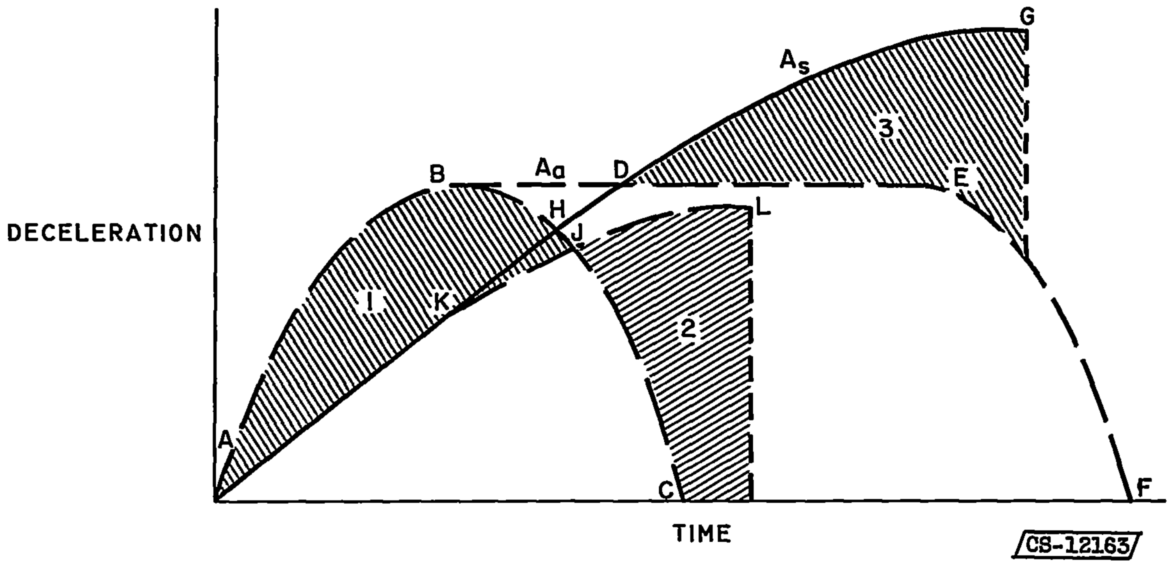
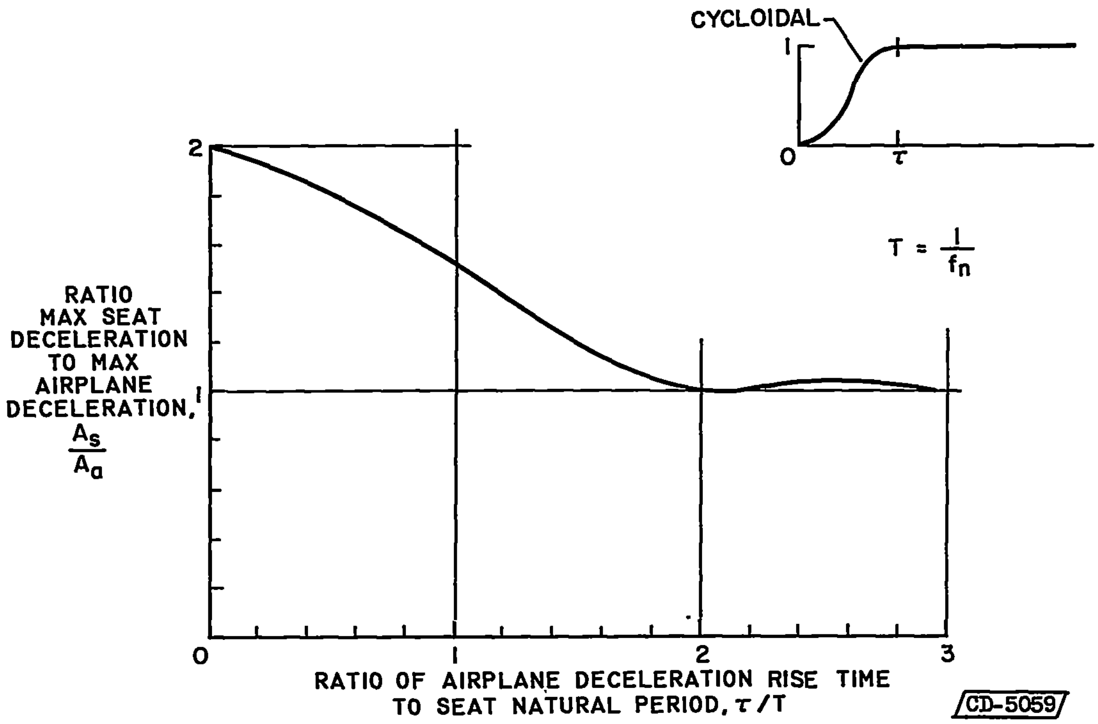


(a) Schematic interpretation of response.



(b) Ratio of maximum seat deceleration to maximum airplane deceleration.

Figure 11. - Seat response, prolonged deceleration pulse.

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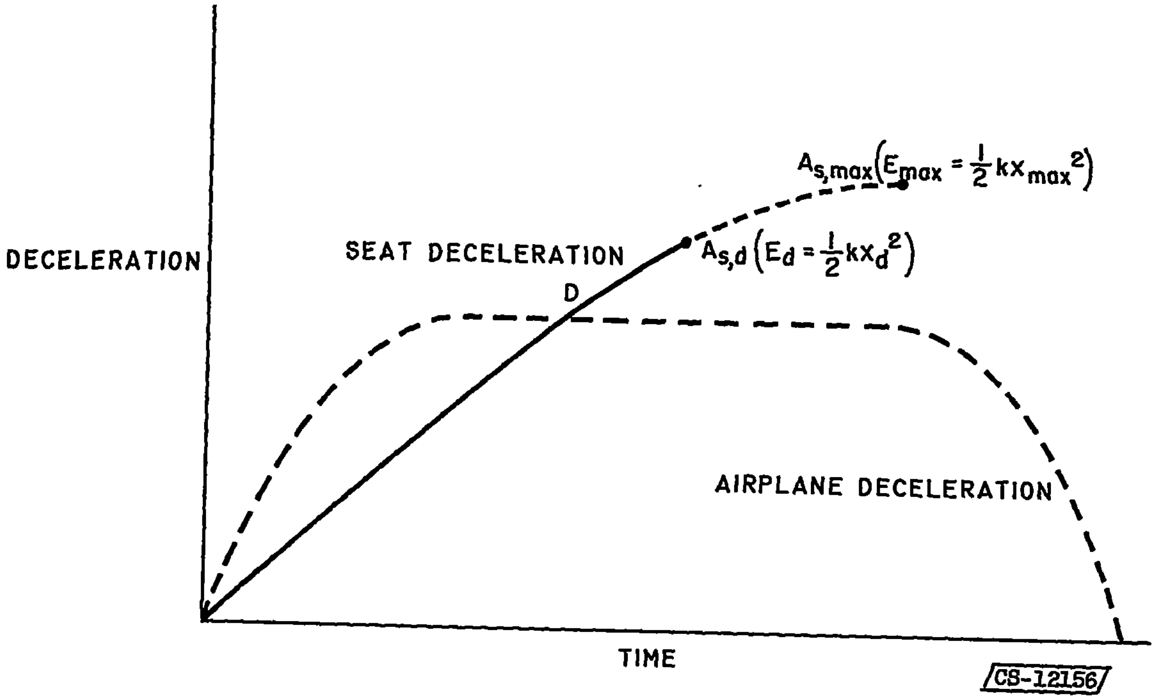

Figure 12. - Energy for seat failure.

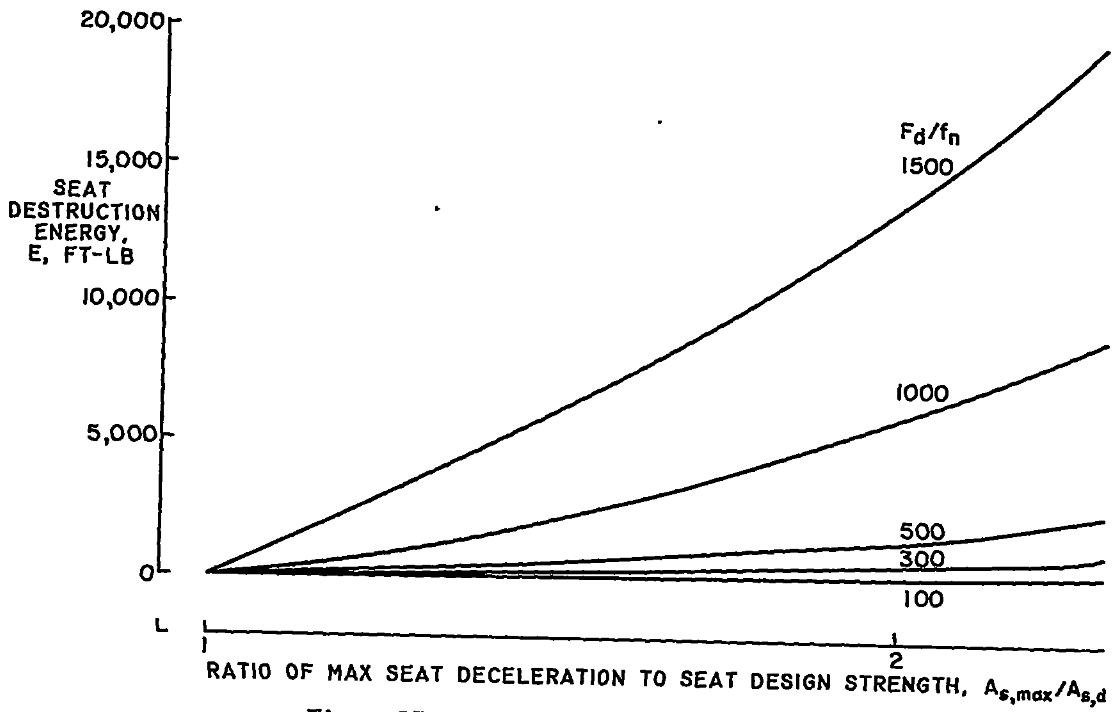

Figure 13. - Energy for seat destruction.

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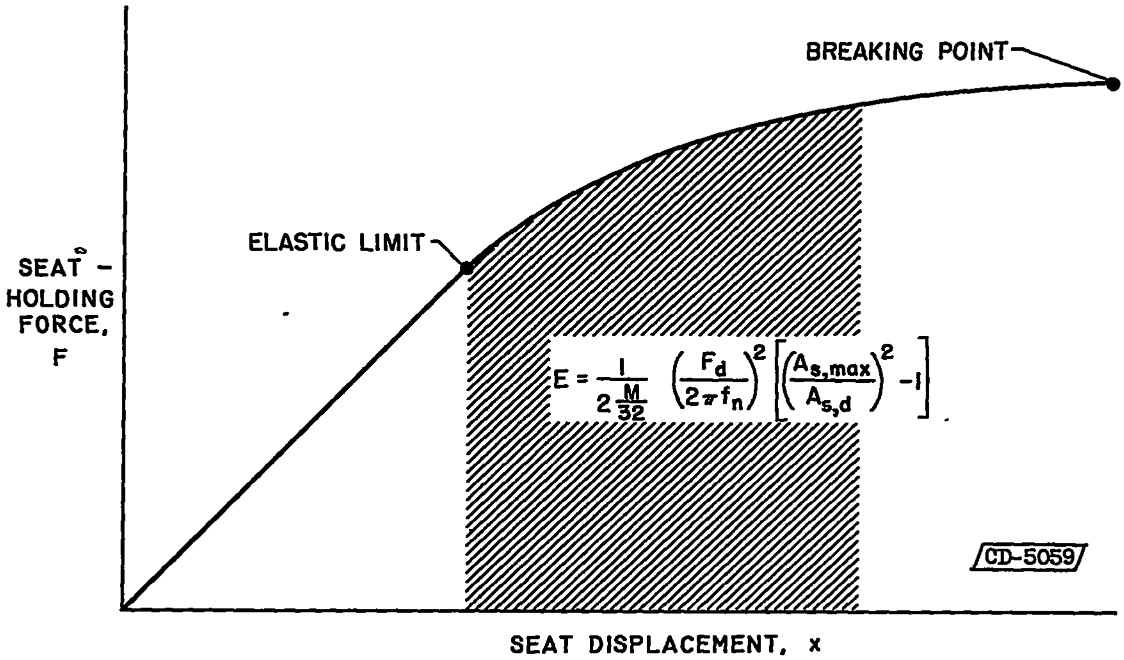
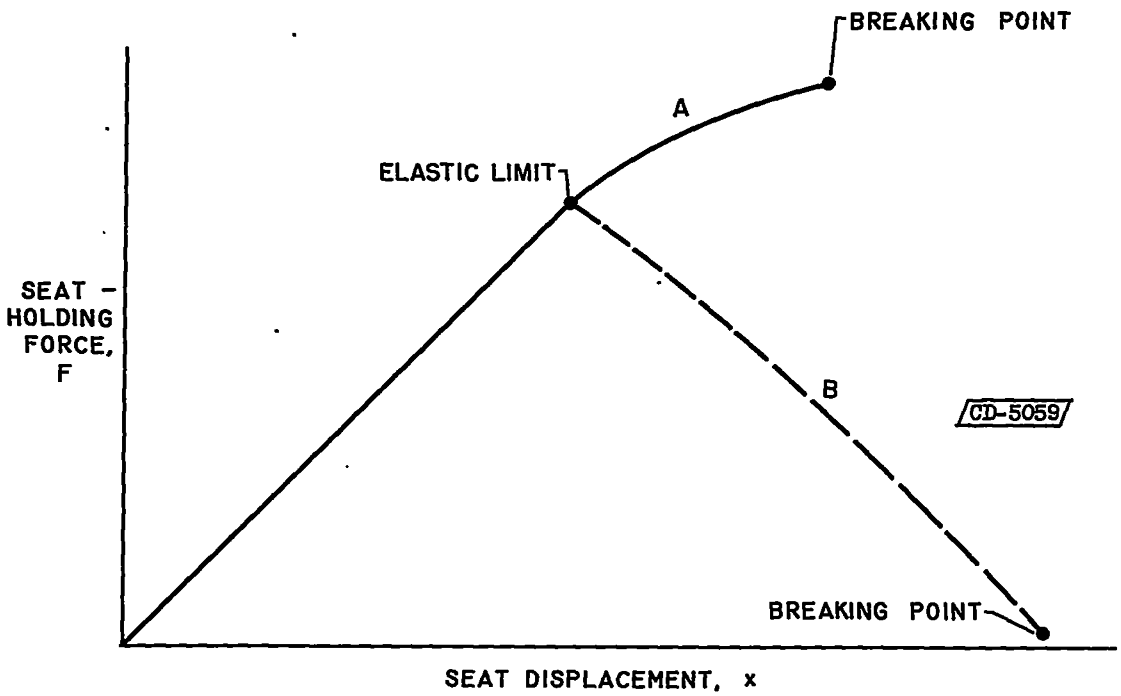
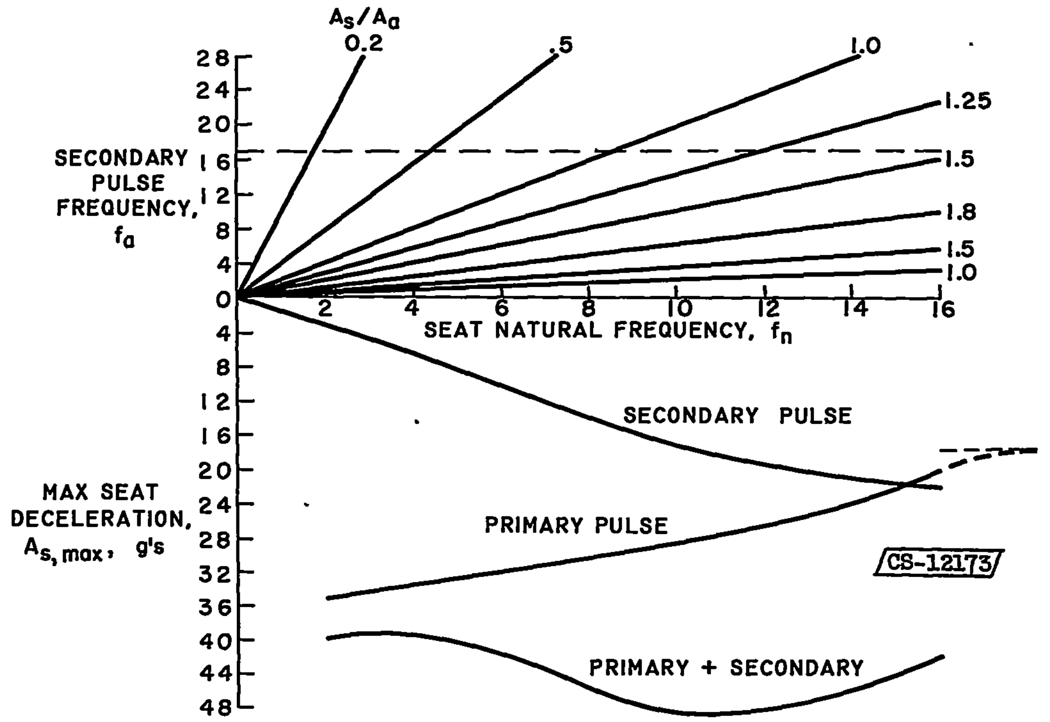


(a) Satisfactory energy-absorption characteristics.

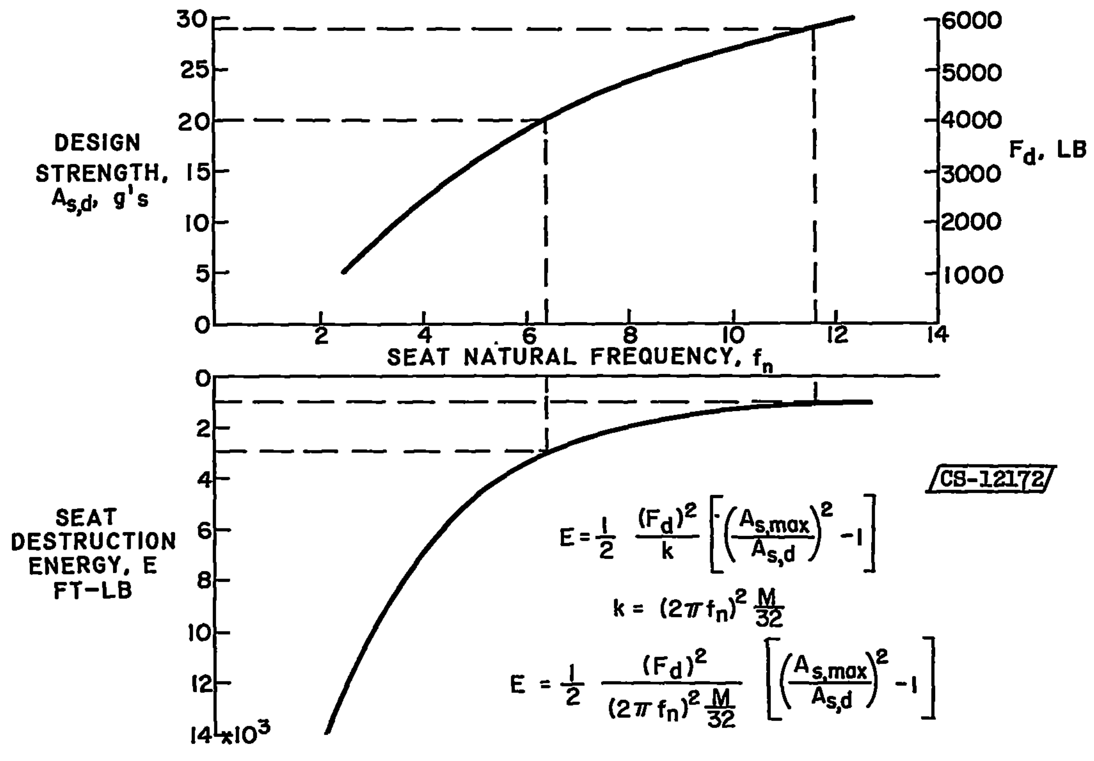


(b) Unsatisfactory energy-absorption characteristics.

Figure 14. - Energy absorption beyond elastic limit.



(a) Determination of maximum seat deceleration.



(b) Determination of seat-destruction energy requirement.

Figure 15. - Seat-design chart.

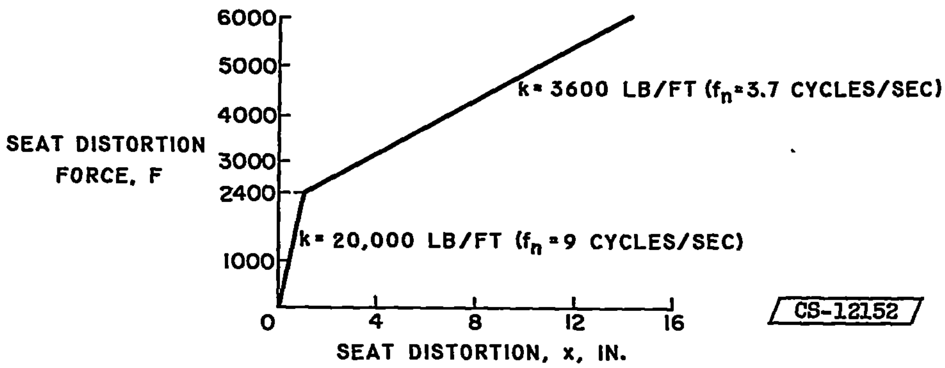


Figure 16. - Duplex seat frequency.

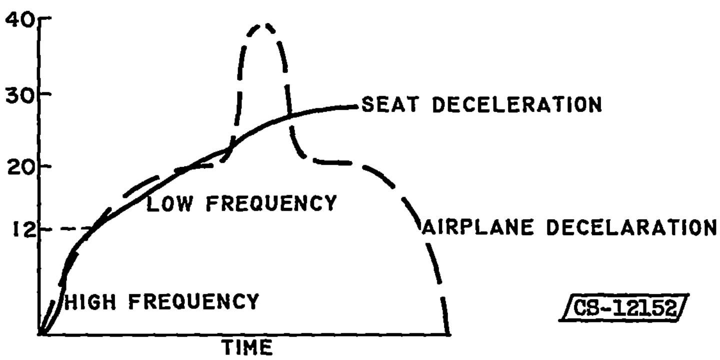


Figure 17. - Duplex-seat response.

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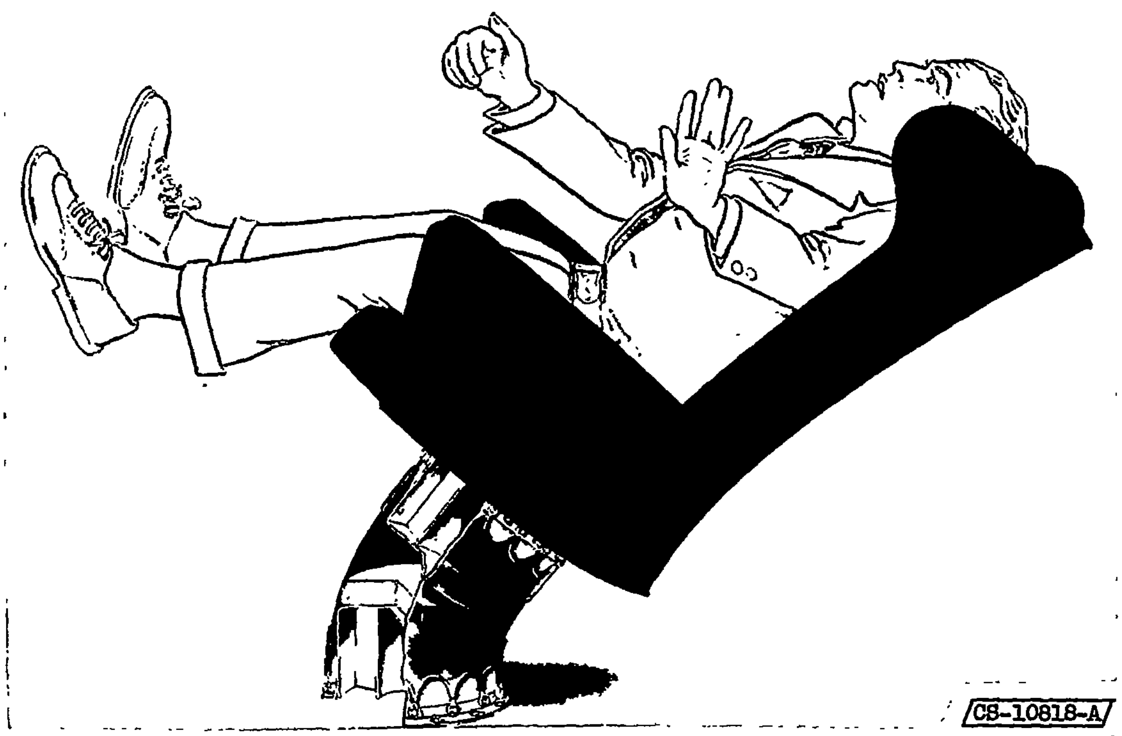

Figure 18. - Experimental duplex seat, impact from rear.

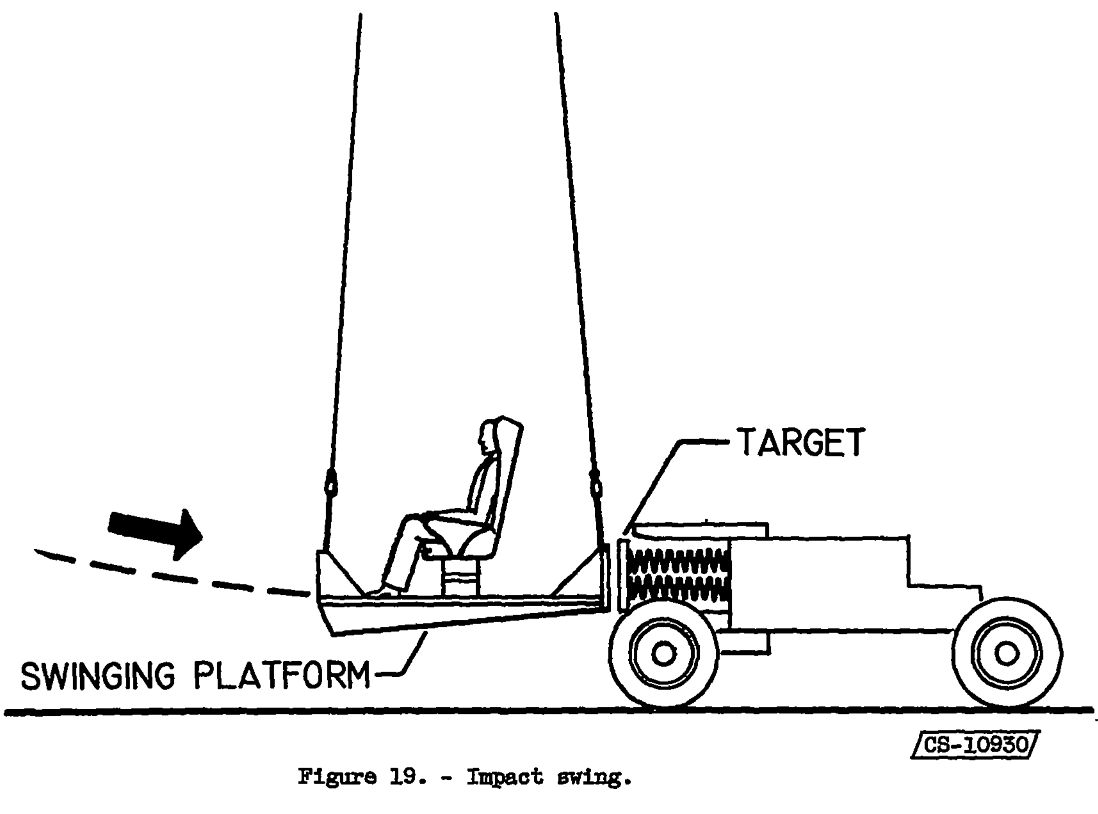

Figure 19. - Impact swing.

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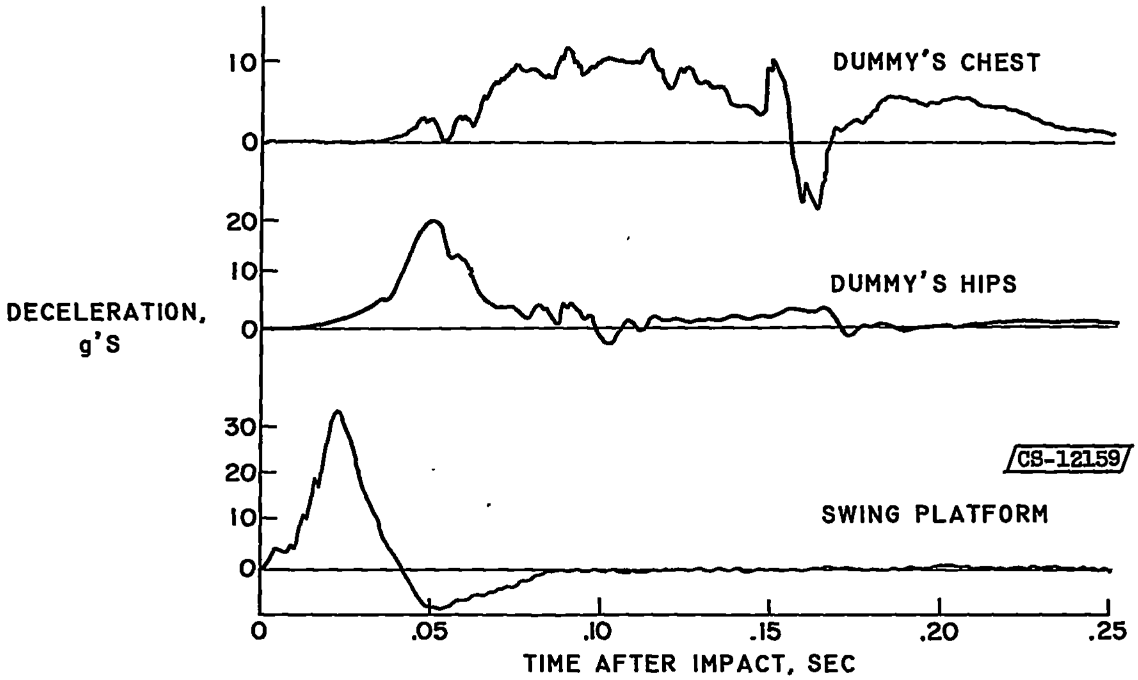

Figure 20. - Measured passenger decelerations; duplex seat, longitudinal deceleration.

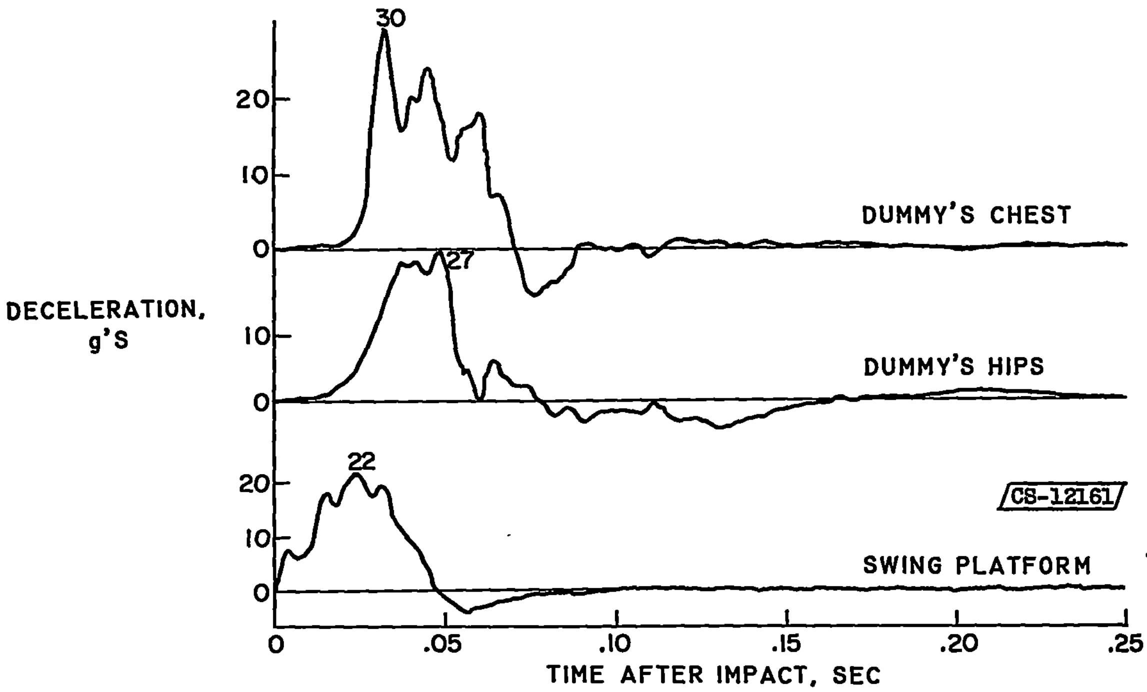

Figure 21. - Measured passenger decelerations; rigid seat, longitudinal deceleration.

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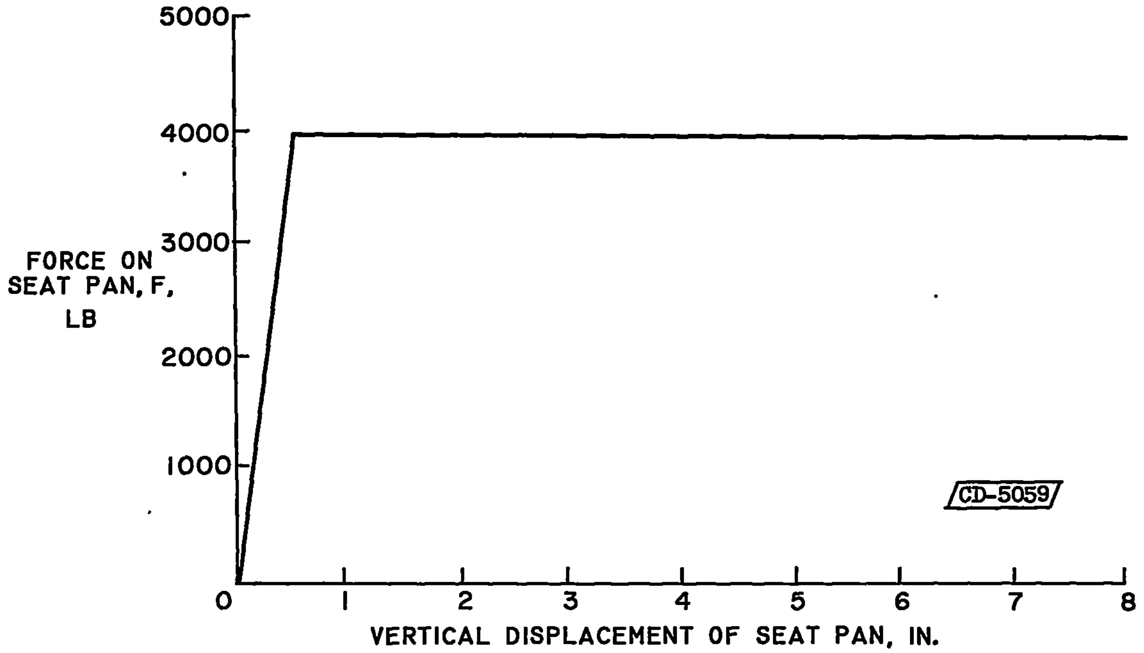
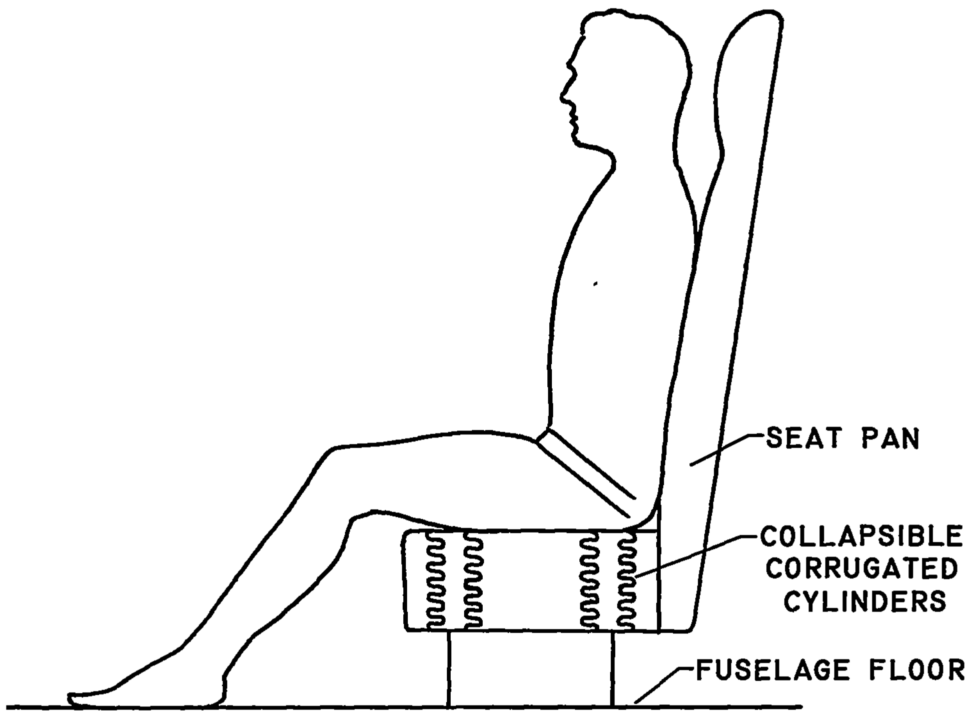


(a) Force-displacement curve for vertical energy absorption.



(b) Corrugated cylinders.

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Figure 22. - Vertical energy absorption.

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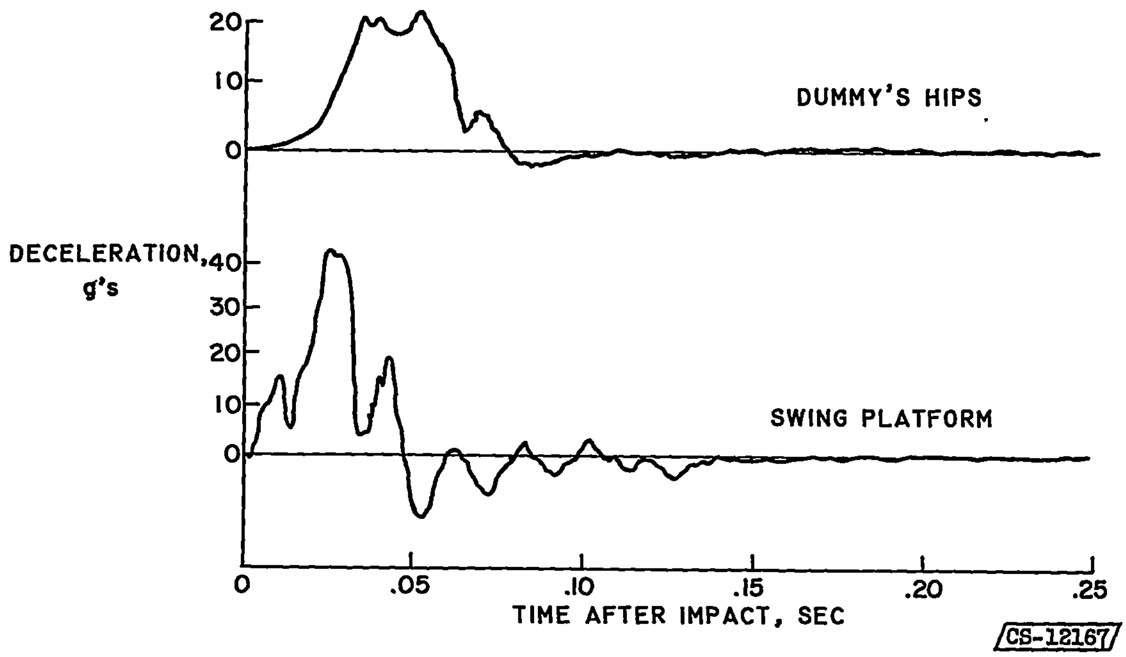

Figure 23. - Measured passenger decelerations; duplex seat, vertical deceleration.

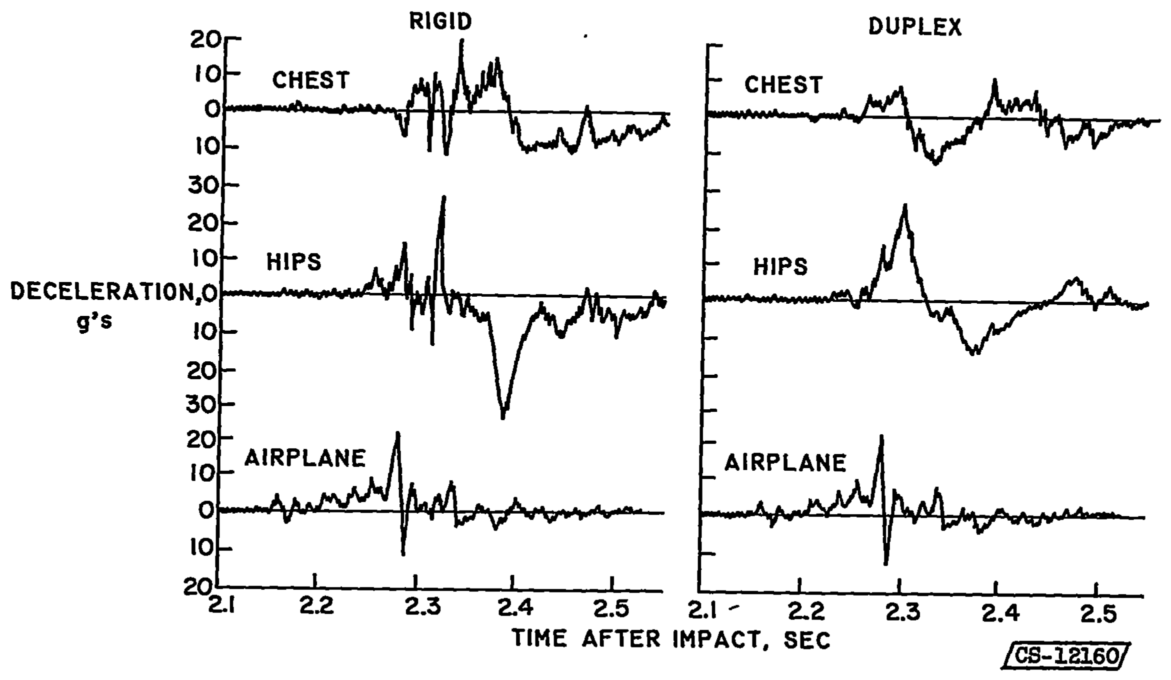

Figure 24. - Measured passenger deceleration; rigid and duplex seats, lateral deceleration.

4150

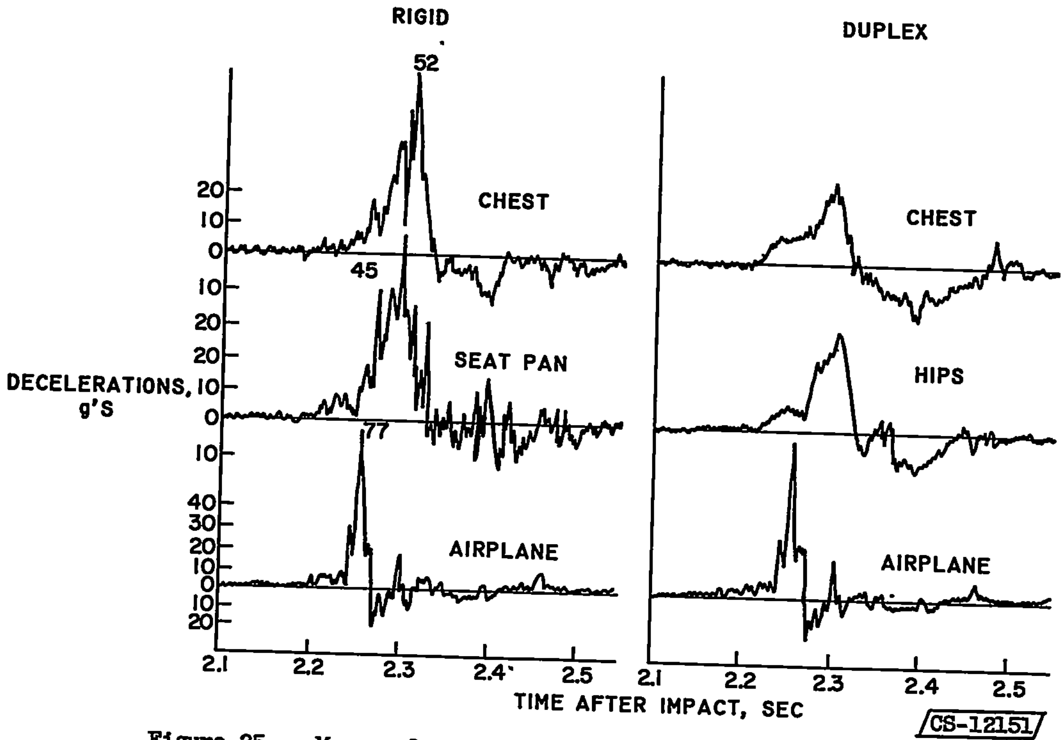

Figure 25. - Measured passenger responce; rigid and duplex seats, vertical deceleration.

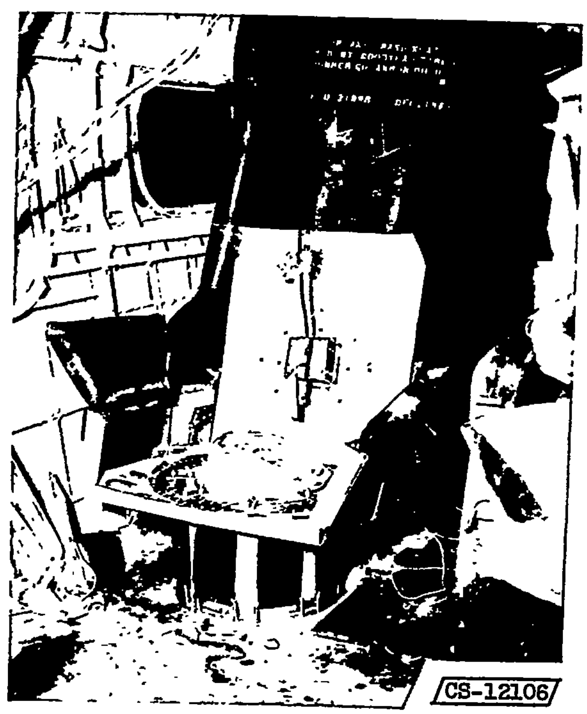

Figure 26. - Compression of corrugated cylinder.

Figure 27. - Seat-pan failure.

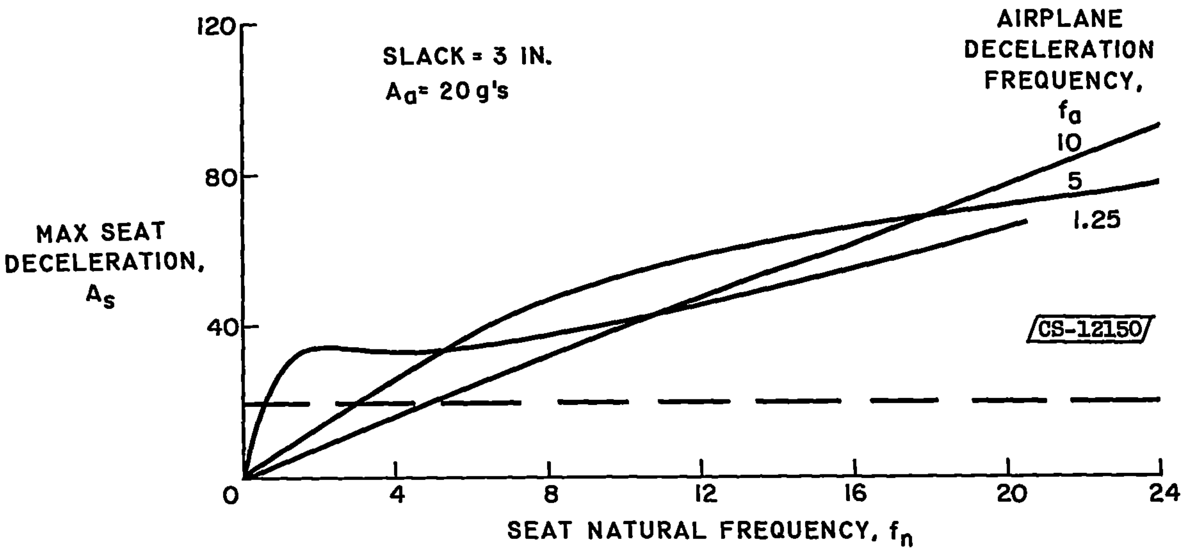

Figure 28. - Effect of seat slack on maximum seat deceleration.